Probing the GeV Emission Mechanism of the Vela Pulsar via Energy-Dependent Light Curve Modeling

C Venter[1], M Barnard[1], AK Harding[2], C Kalapotharakos[1,3]

[1]Centre for Space Research, North-West University, Potchefstroom, South Africa

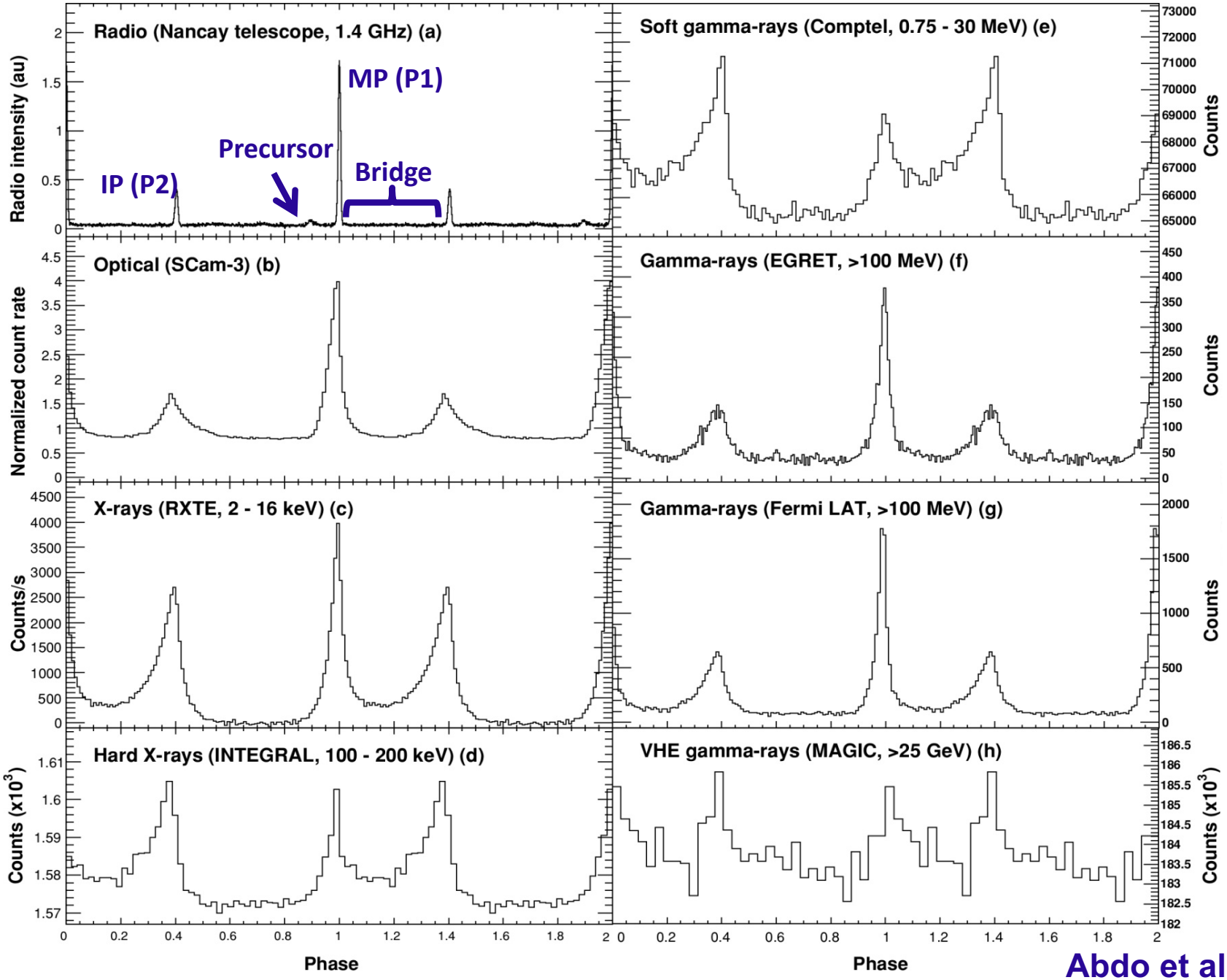
[2]NASA Goddard Space Flight Center, MD, USA

[3]University of Maryland, College Park (UMCP/CRESST), College Park, MD, USA

Workshop on Magnetospheres of NSs and BHs

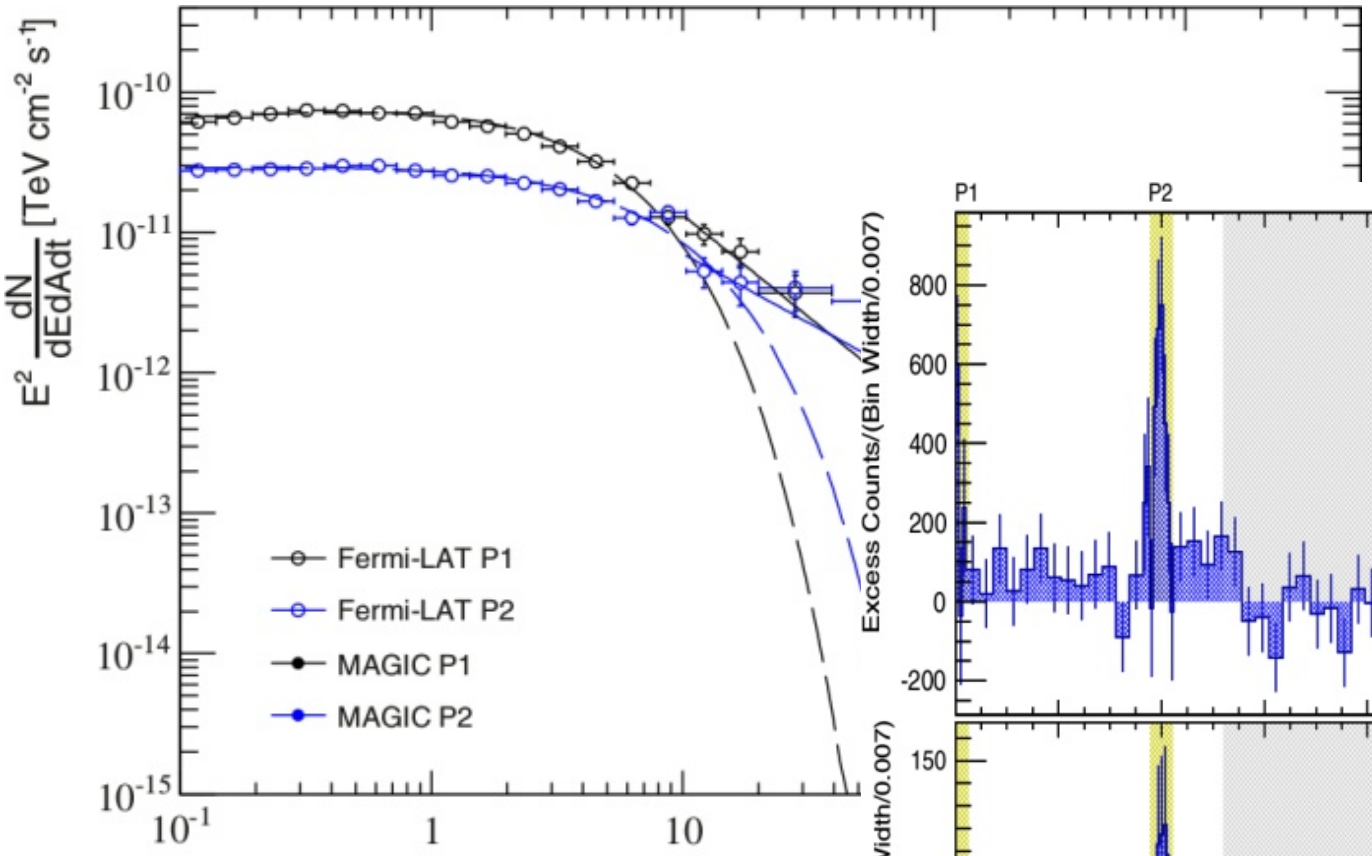
NASA Goddard Space Flight Center, 10 – 13 June 2019

Energy-dependent LCs: Crab Pulsar

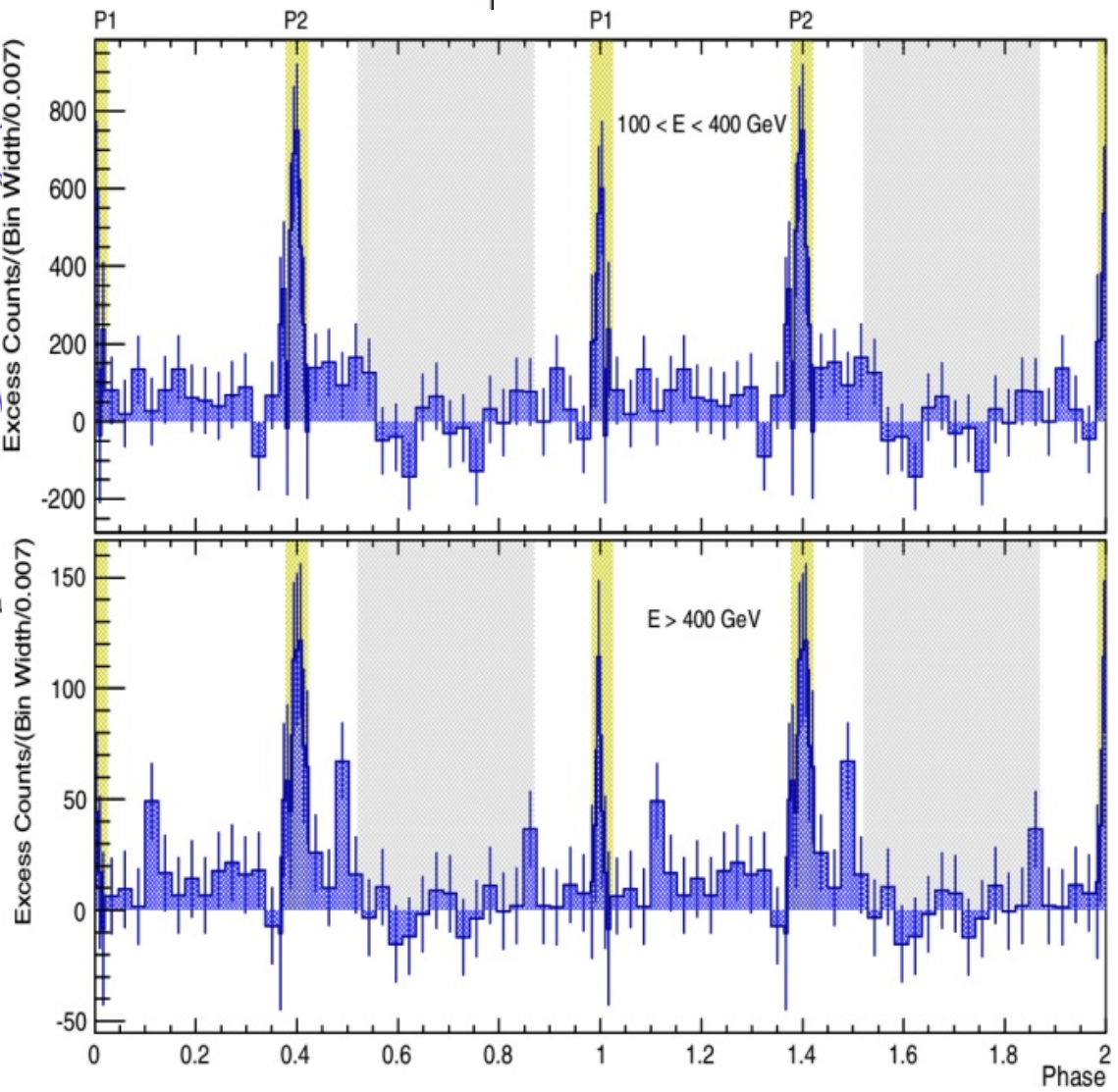


Abdo et al. (2010)

Pulsed TeV Emission from the Crab PSR

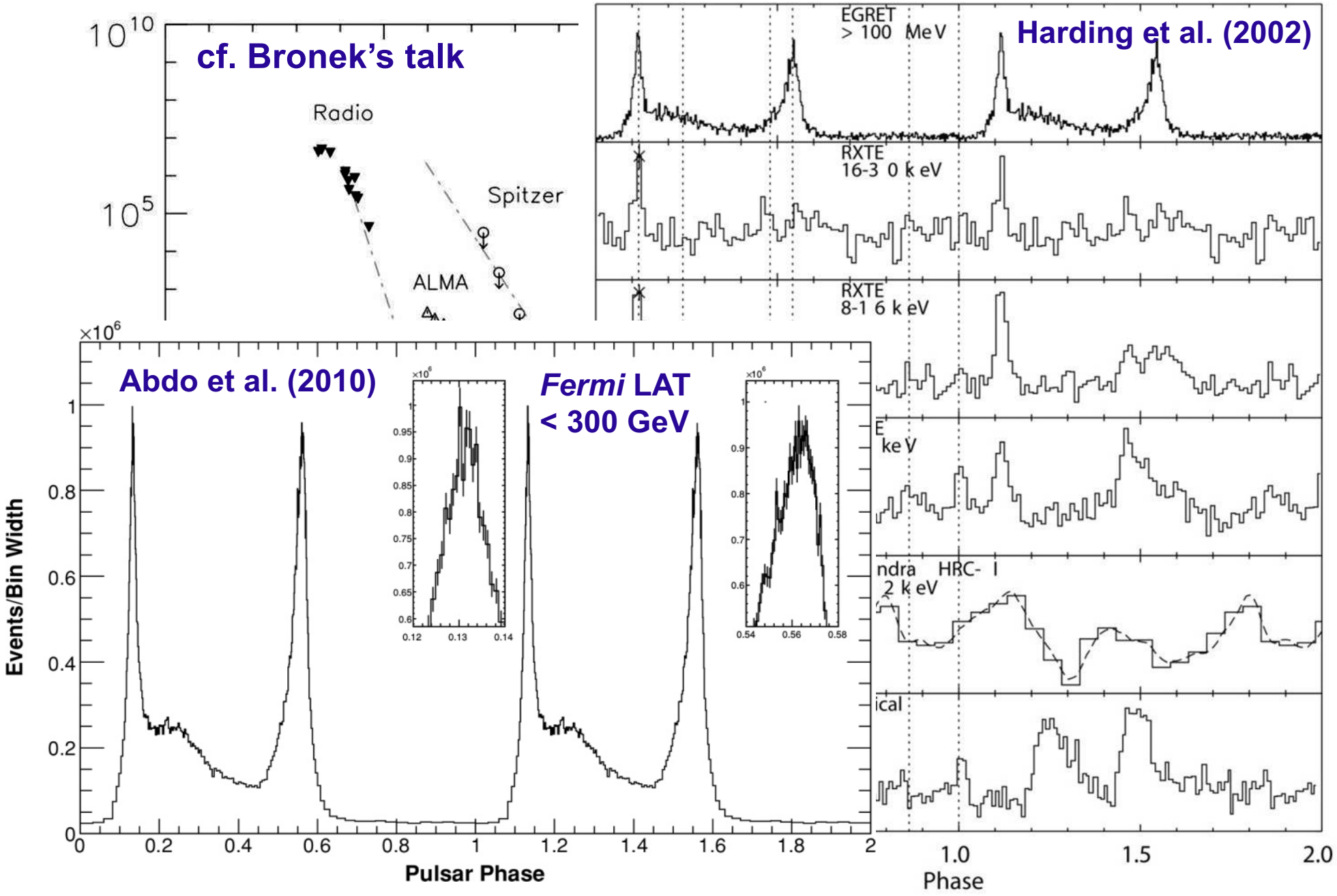


Ansoldi et al. (2016)



- **Detection up to 1.5 TeV**
- **Both P1 and P2 still visible**

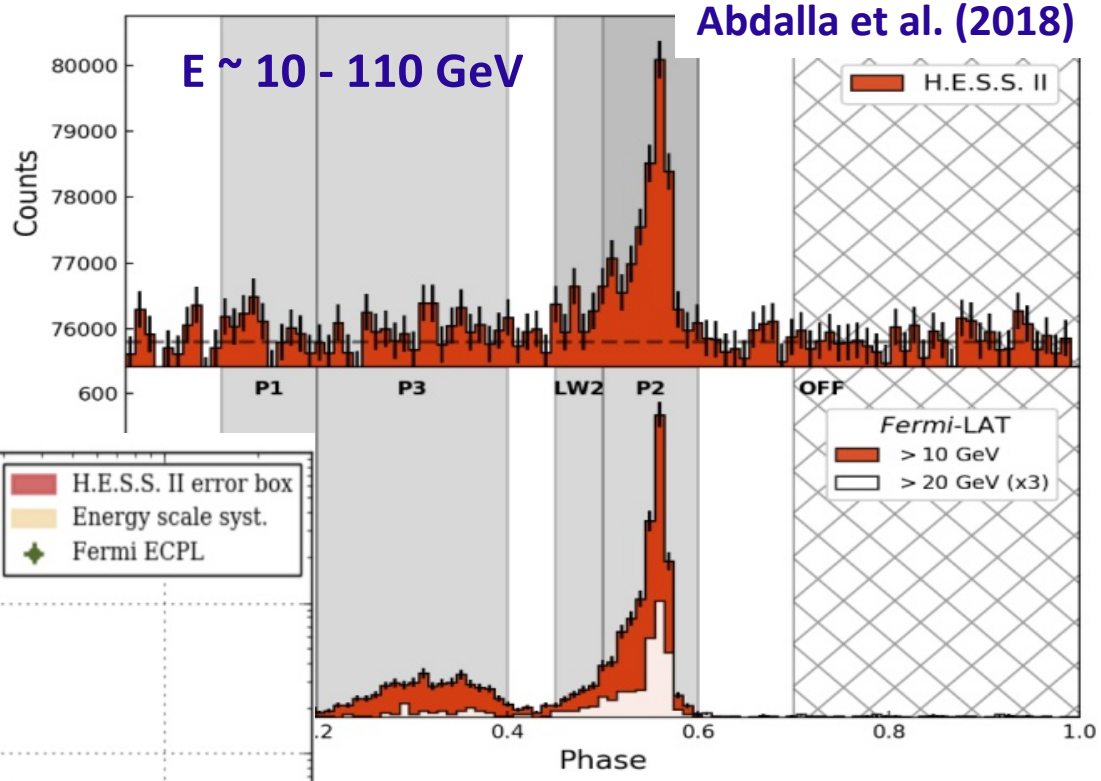
Energy-dependent LCs: Vela Pulsar

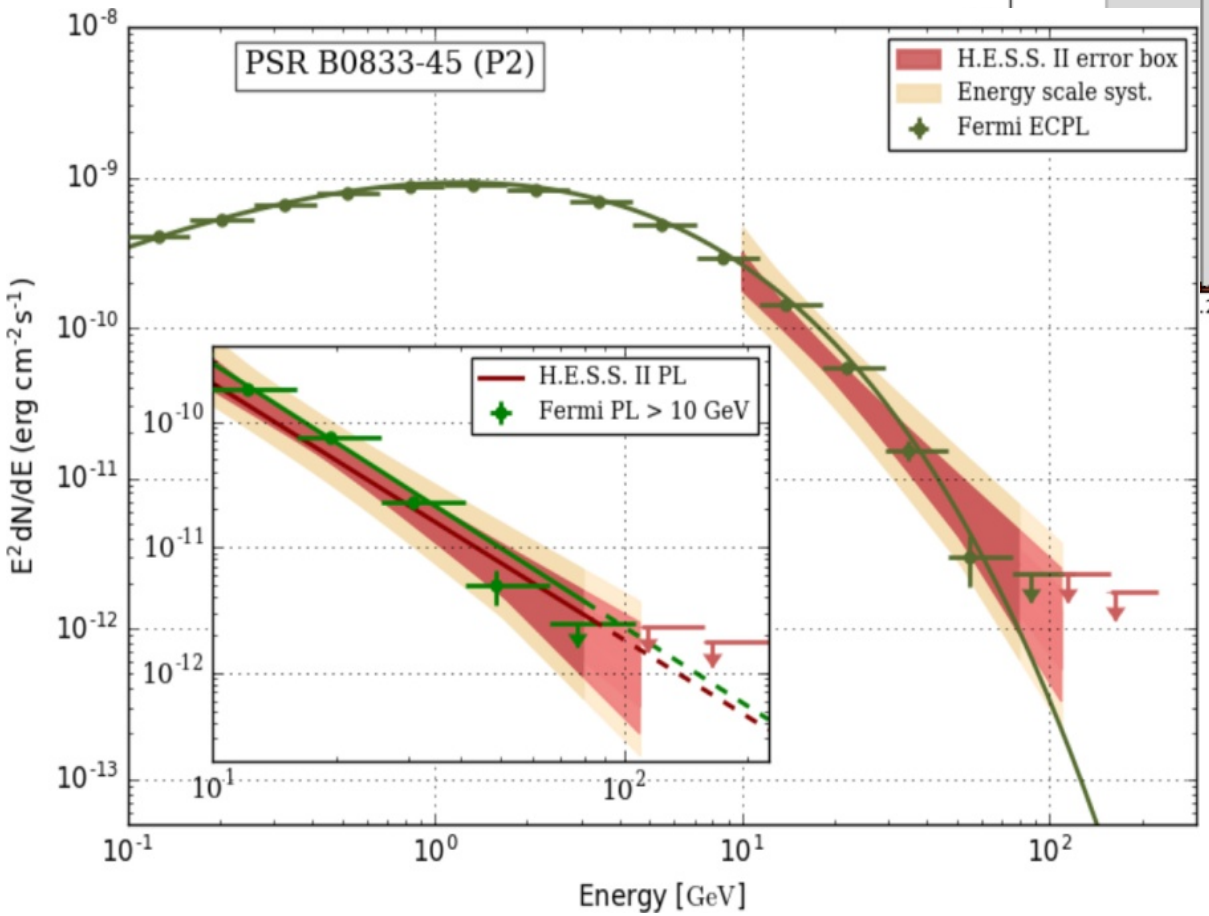


Pulsed TeV Emission from Vela PSR

- **3 – 7 TeV.**
- **P2 detected at 5.6σ level and P1 not visible.**

Abdalla et al. (2018)



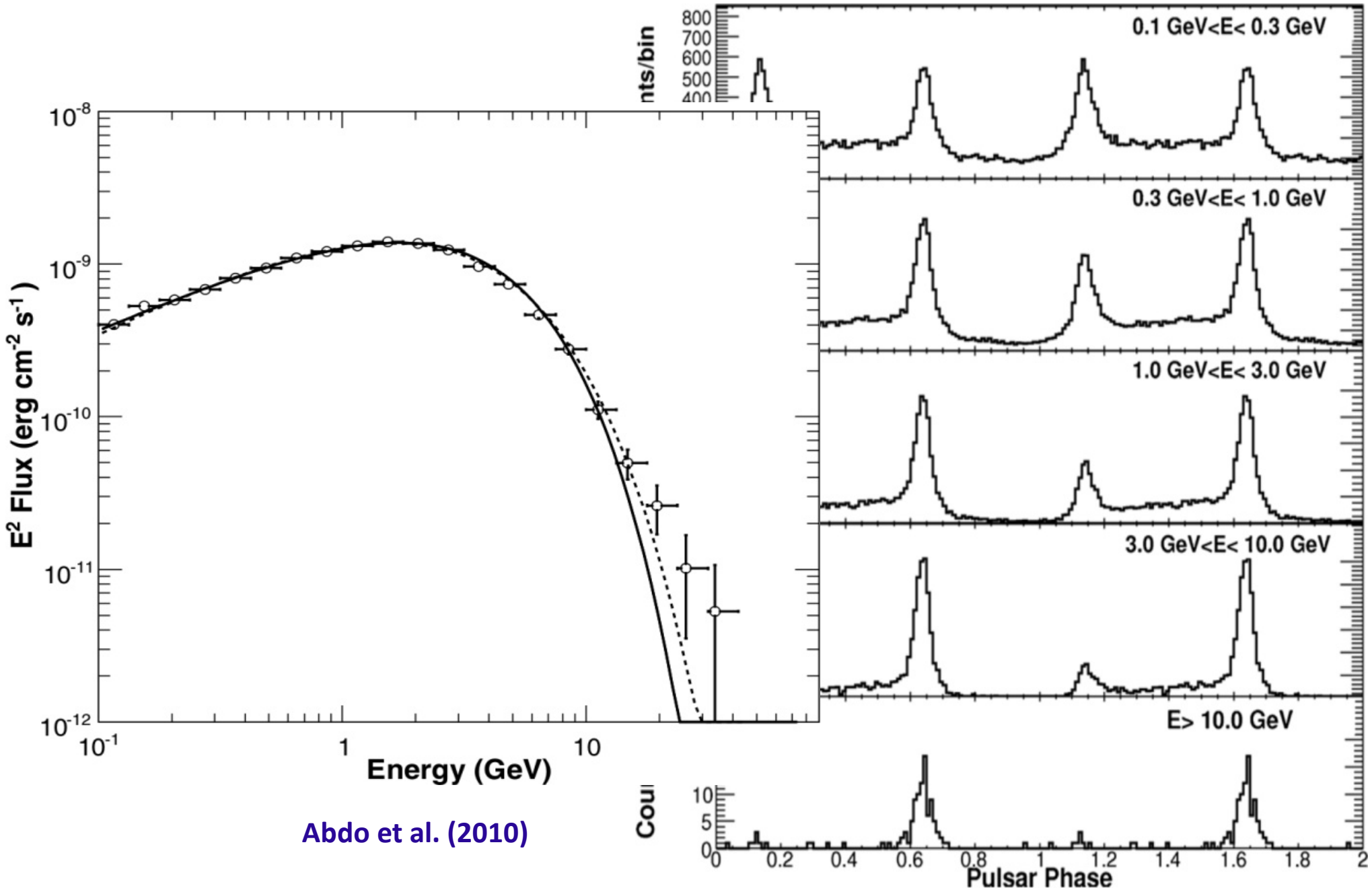


MOTIVATION:

Curved spectrum favoured by H.E.S.S. (>3σ).

CR tail or a different component?

Energy-dependent LCs: Geminga Pulsar

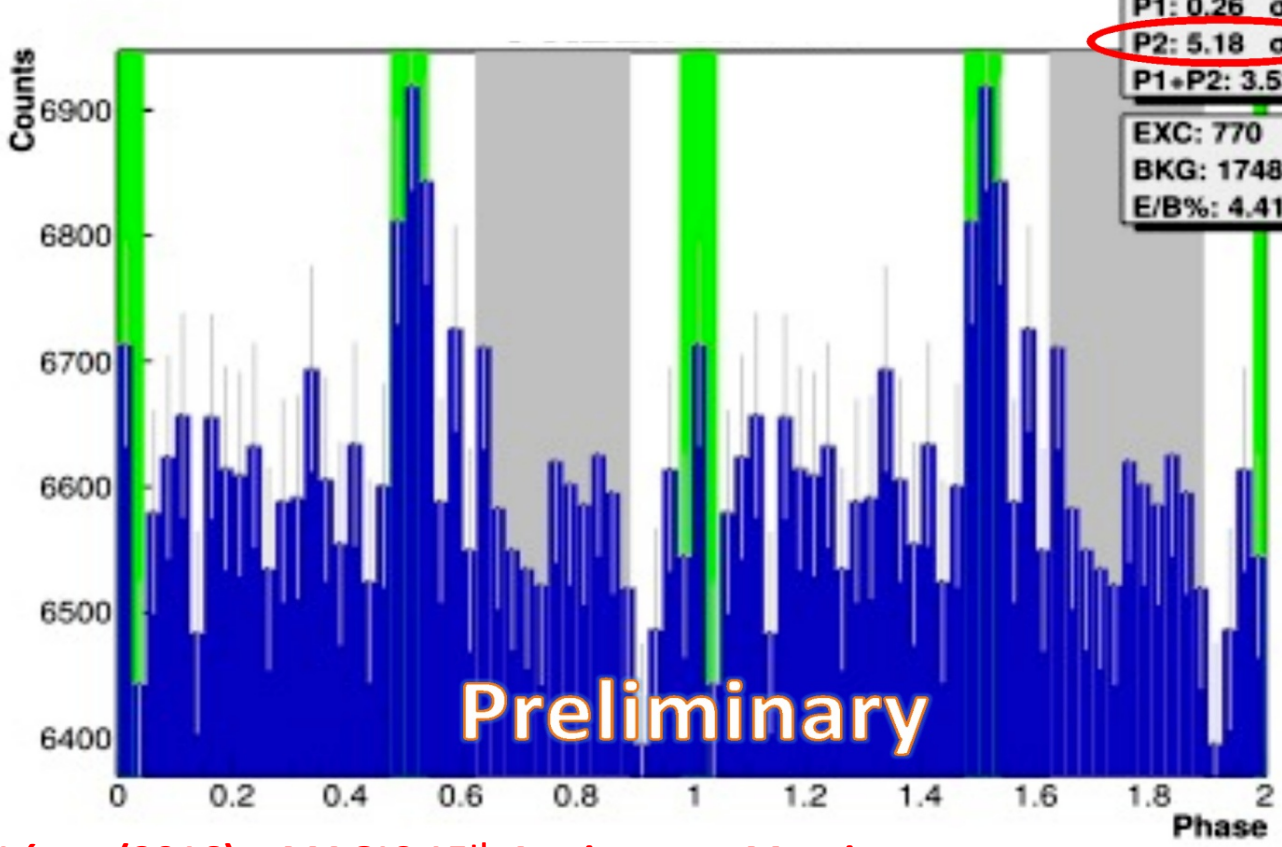


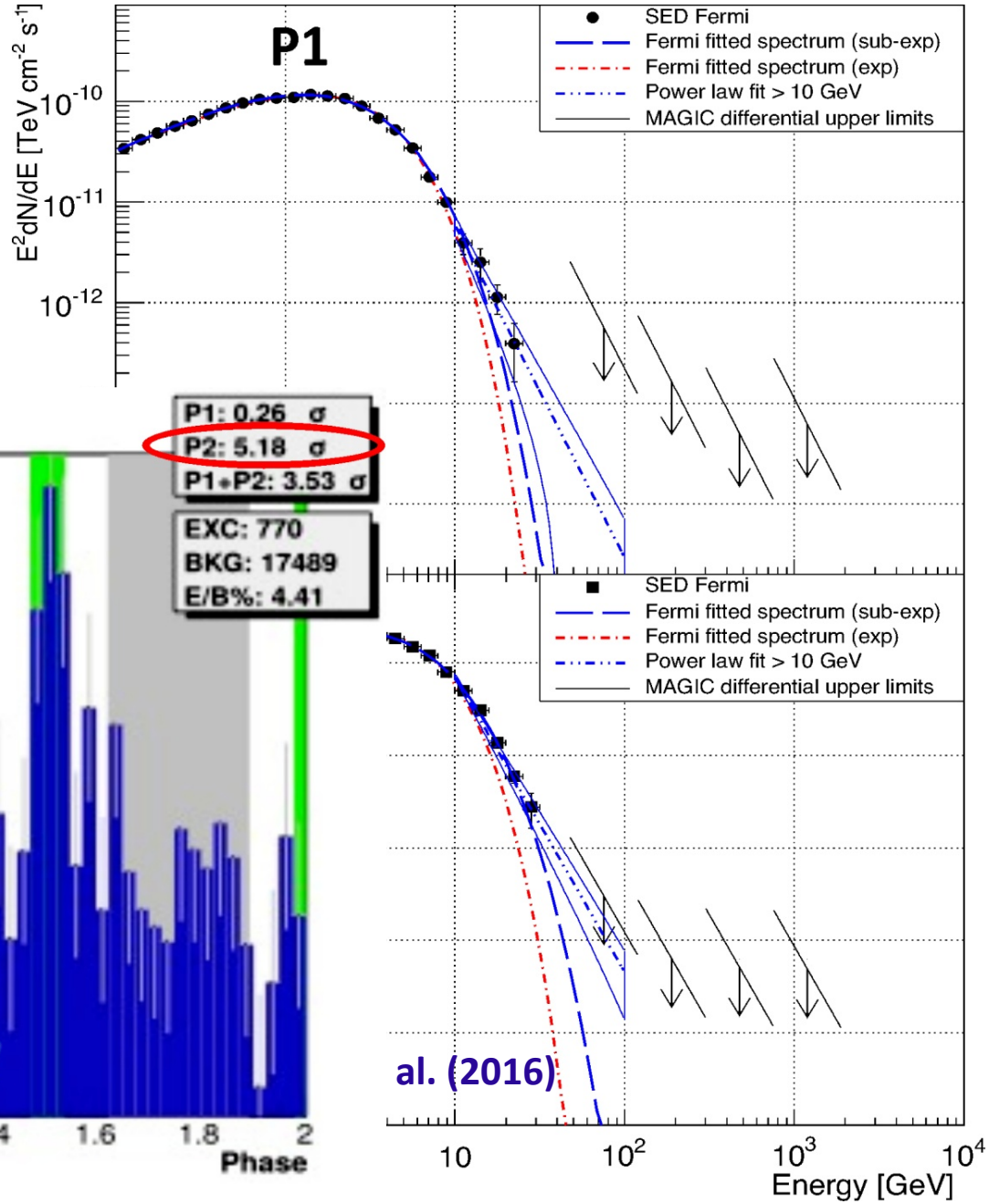
Abdo et al. (2010)

Pulsed (Sub) TeV emission from Geminga

- **Previous ULs didn't rule out VHE power-law tail.**
- **Pulsations >50 GeV:**

  P2 detected at 5σ level, P1 not visible.





al. (2016)

López (2016) – MAGIC 15th Anniversary Meeting

Some Open Questions

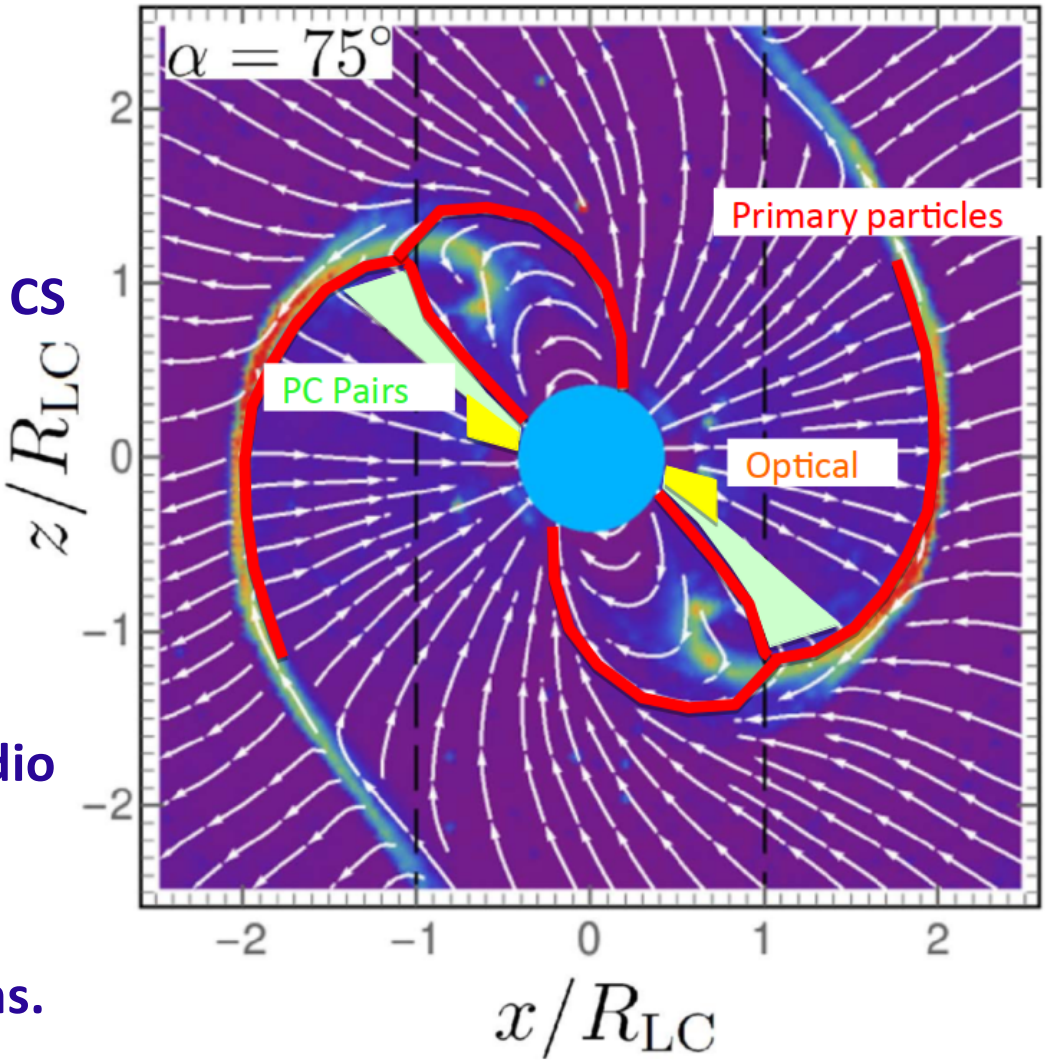
- **Spectral shape of emitting particles (primaries / pairs)?**
- **Which emission mechanisms contribute to the broadband SED?**
- **Local and global electrodynamical properties?**
- **Pulsar (magnetosphere) geometry?**

Spectral and energy-dependent light curve modelling
(Polarimetry)

cf. Diego's talk

Emission Model

- Force-free magnetosphere (Next: FIDO?).
- Pairs and primaries from steady cascade in offset-PC field (Harding & Muslimov 2011a,b).
- Primaries accelerated only in SG and CS (out to $r = 2R_{LC}$) assuming a constant *E*-field.
- No pair acceleration.
- Chosen pair multiplicity.
- Empirical radio core / cone model.
- Resonant cyclotron absorption of radio photons (cf. Lyubarski & Petrova 1998).
- Solve particle dynamics.
- CR, SR, ICS, SSC radiation mechanisms. Focus on primary CR.
- Inertial observer frame.
- Energy-dependent light curves and spectra.

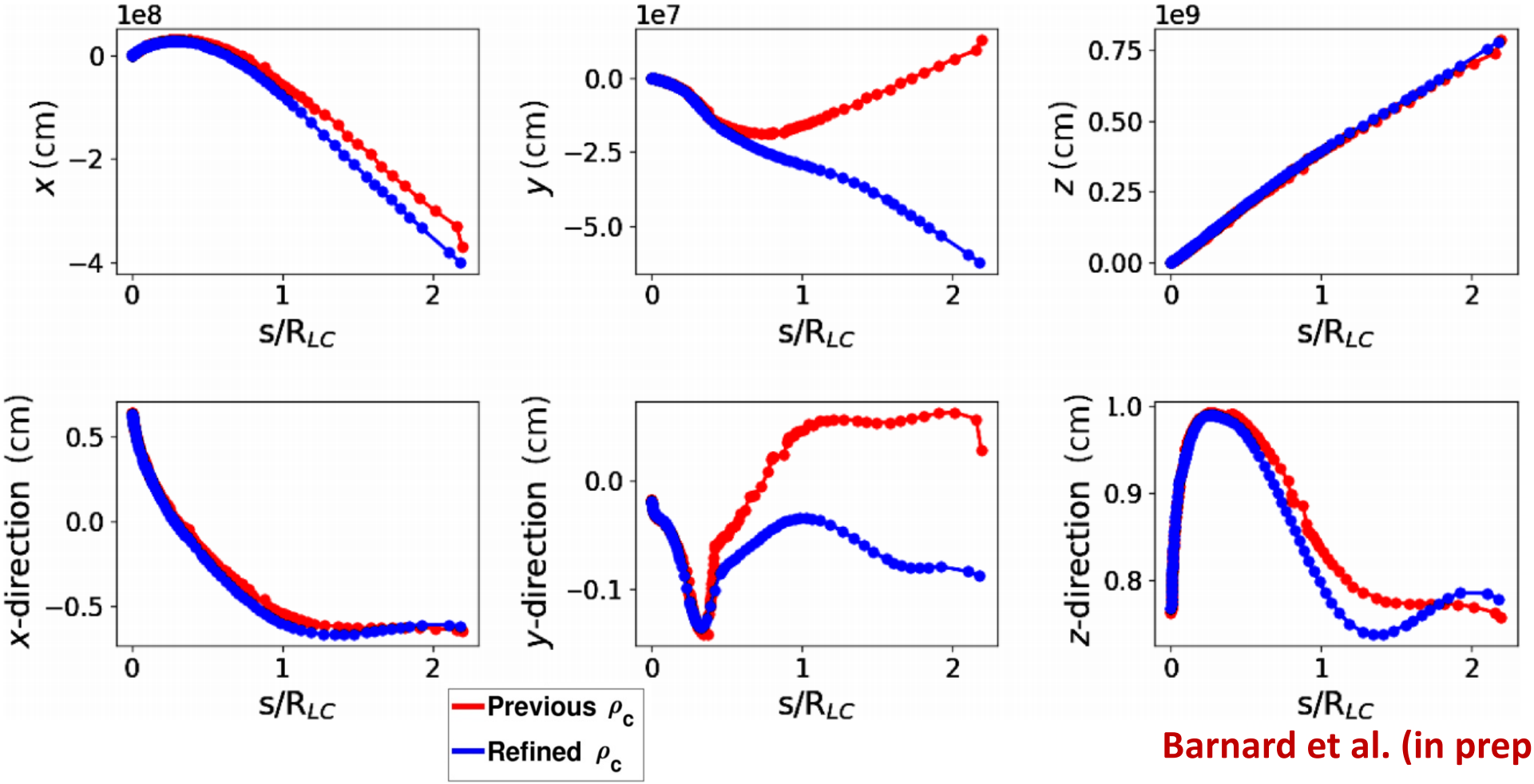


Harding & Kalapotharakos (2015)
Harding et al. (2018)

cf. Alice's talk

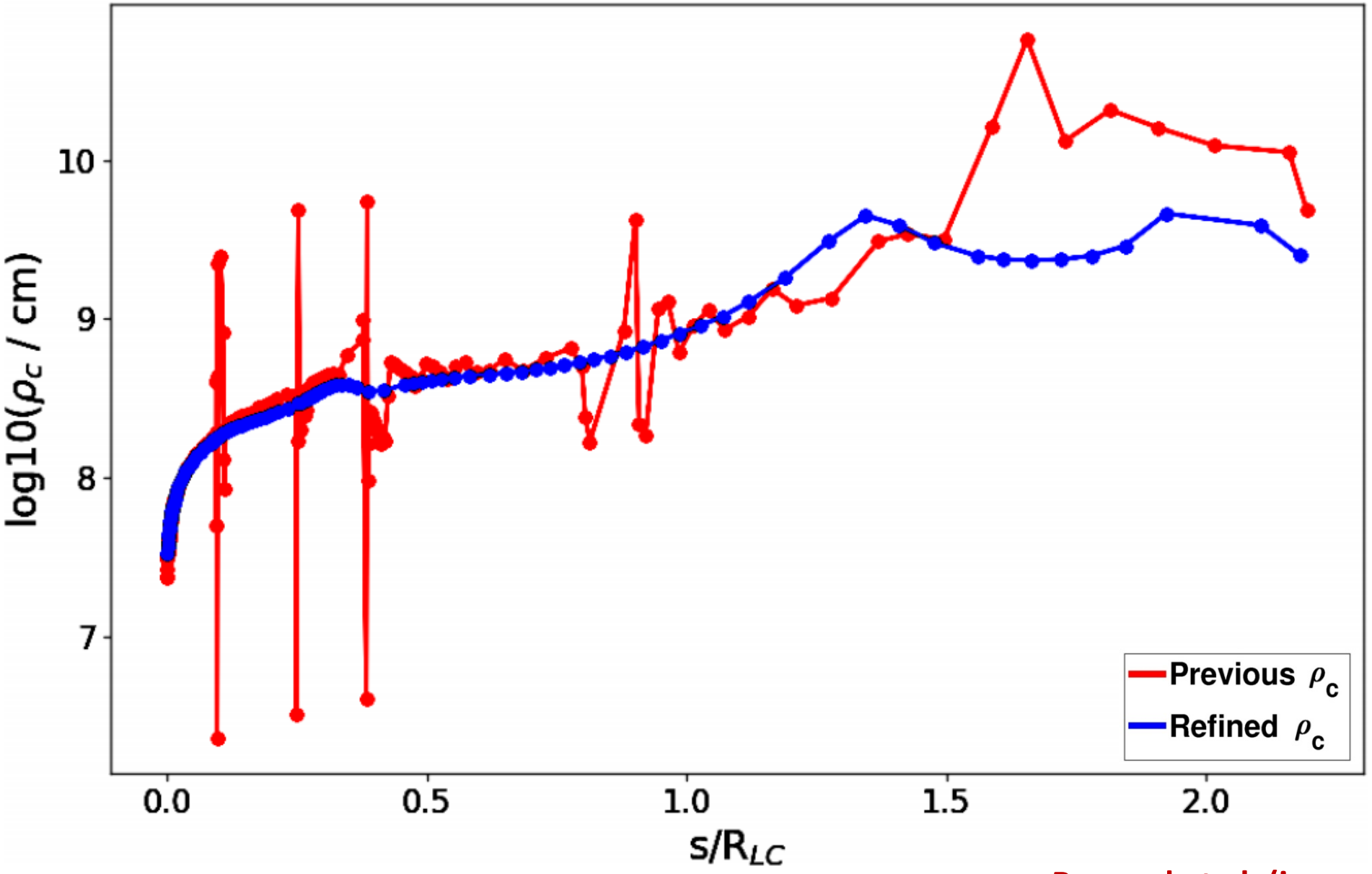
Refinement of Curvature Radius ρ_c

- **Previous:** adaptive step size; calculate ρ_c on the fly. Simultaneous transport
- **Now:** Decouple ρ_c and transport calculation
  - Use fixed, small step size
  - Smooth tangents
  - Obtain second-order derivatives using Lagrange polynomial – precalculate ρ_c; interpolate later



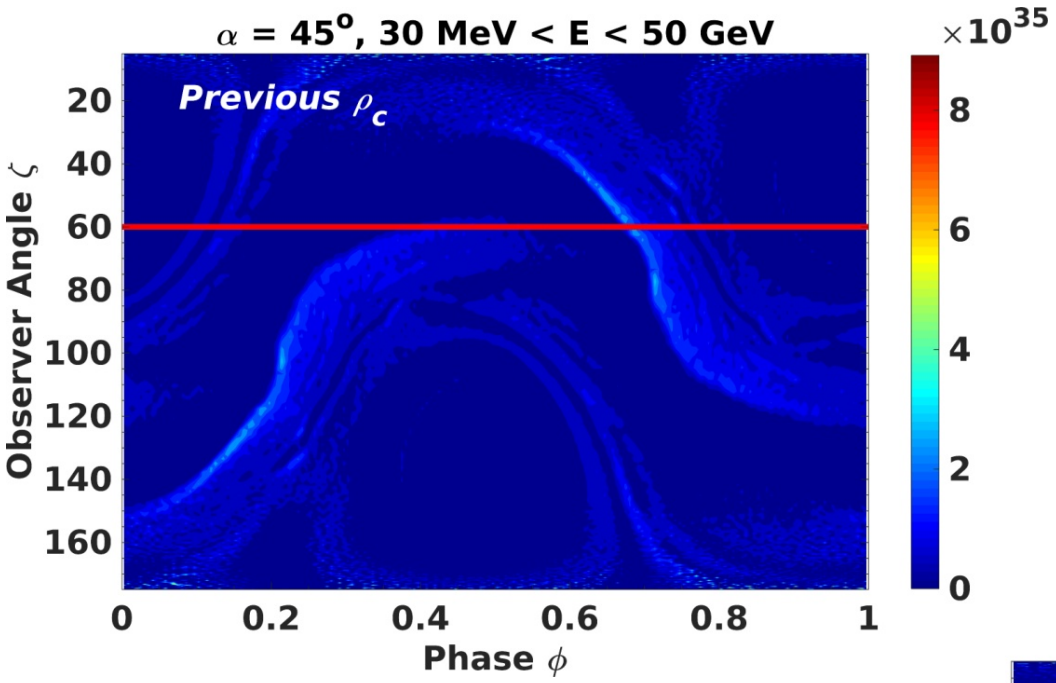
Barnard et al. (in prep)

Refinement of Curvature Radius ρ_c



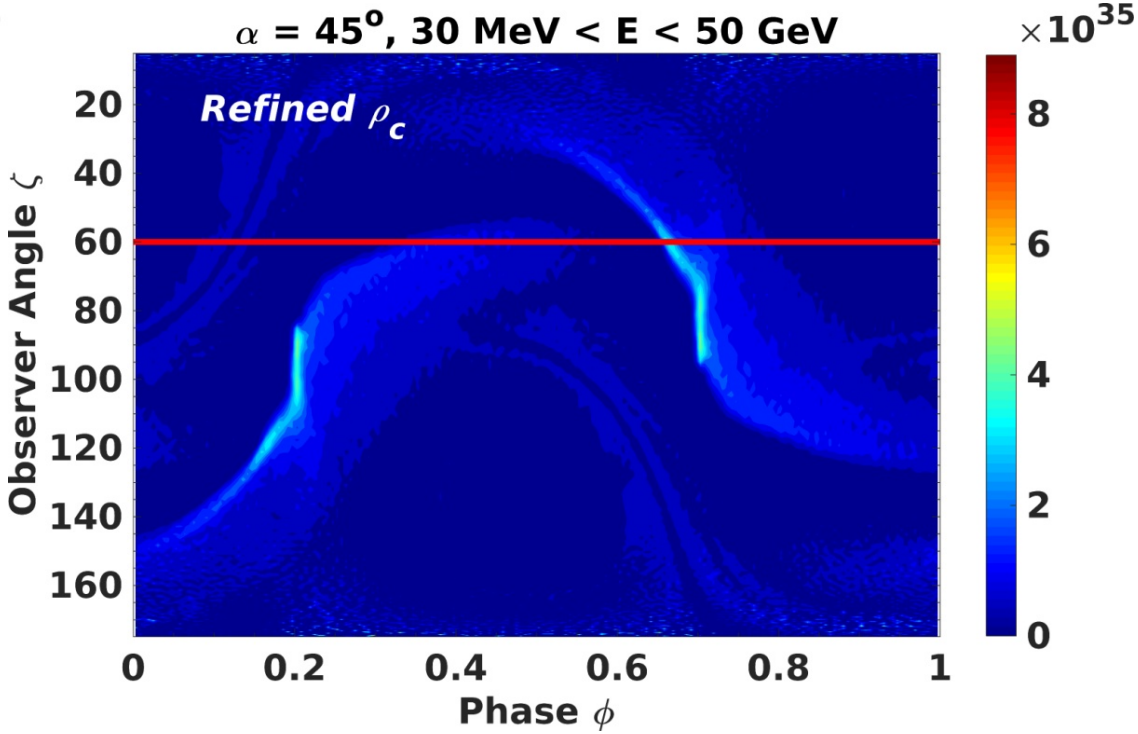
Barnard et al. (in prep)

Refinement of Curvature Radius ρ_c

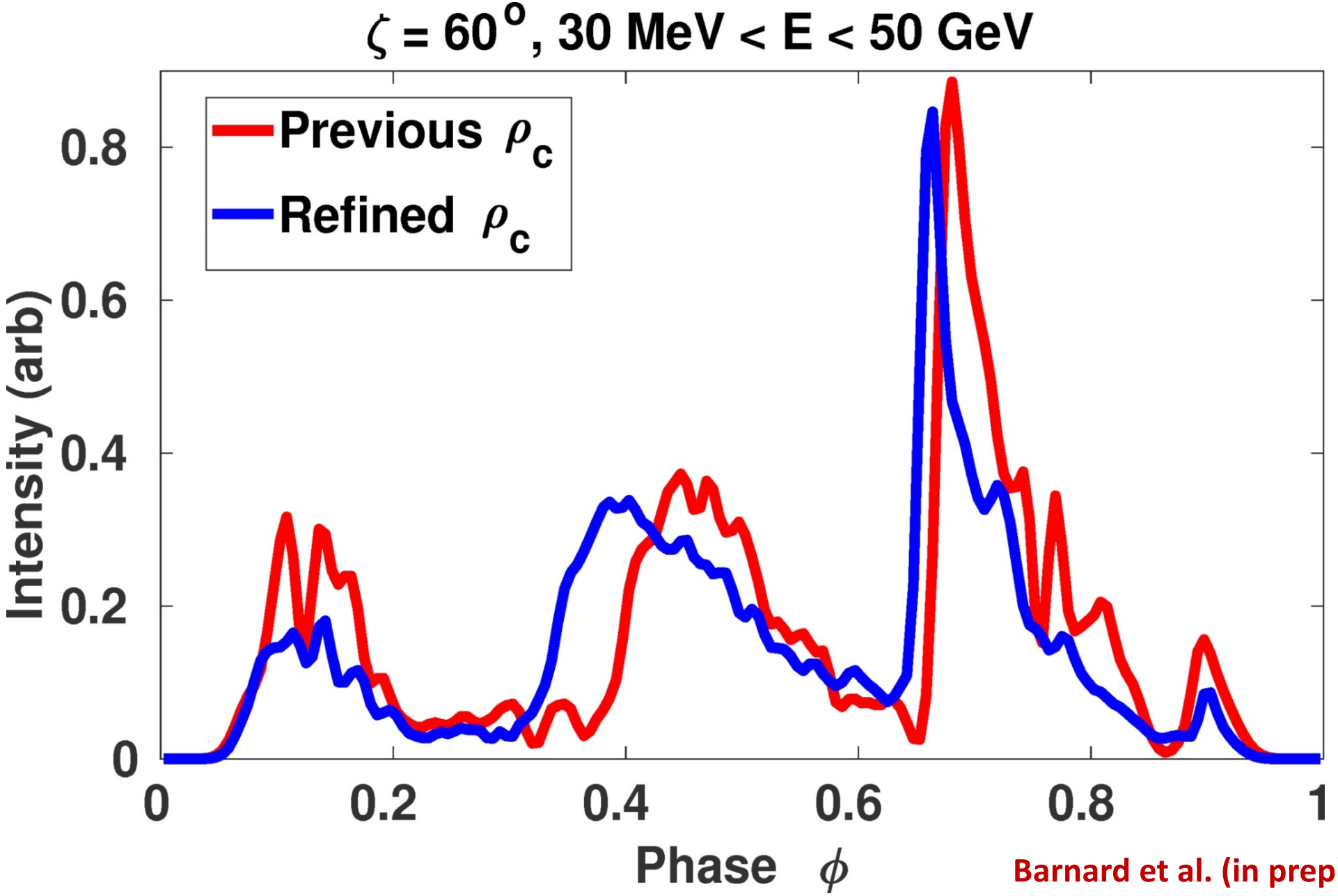


$$\gamma_{\rm RR} = \left(\frac{3E_{||}\rho_c^2}{2e\beta_r^3}\right)^{1/4}$$

$$E_{\gamma,\,\rm cutoff} \sim 4\,E_{||,4}^{3/4}\,\rho_{c,8}^{1/2} \quad \text{GeV}$$



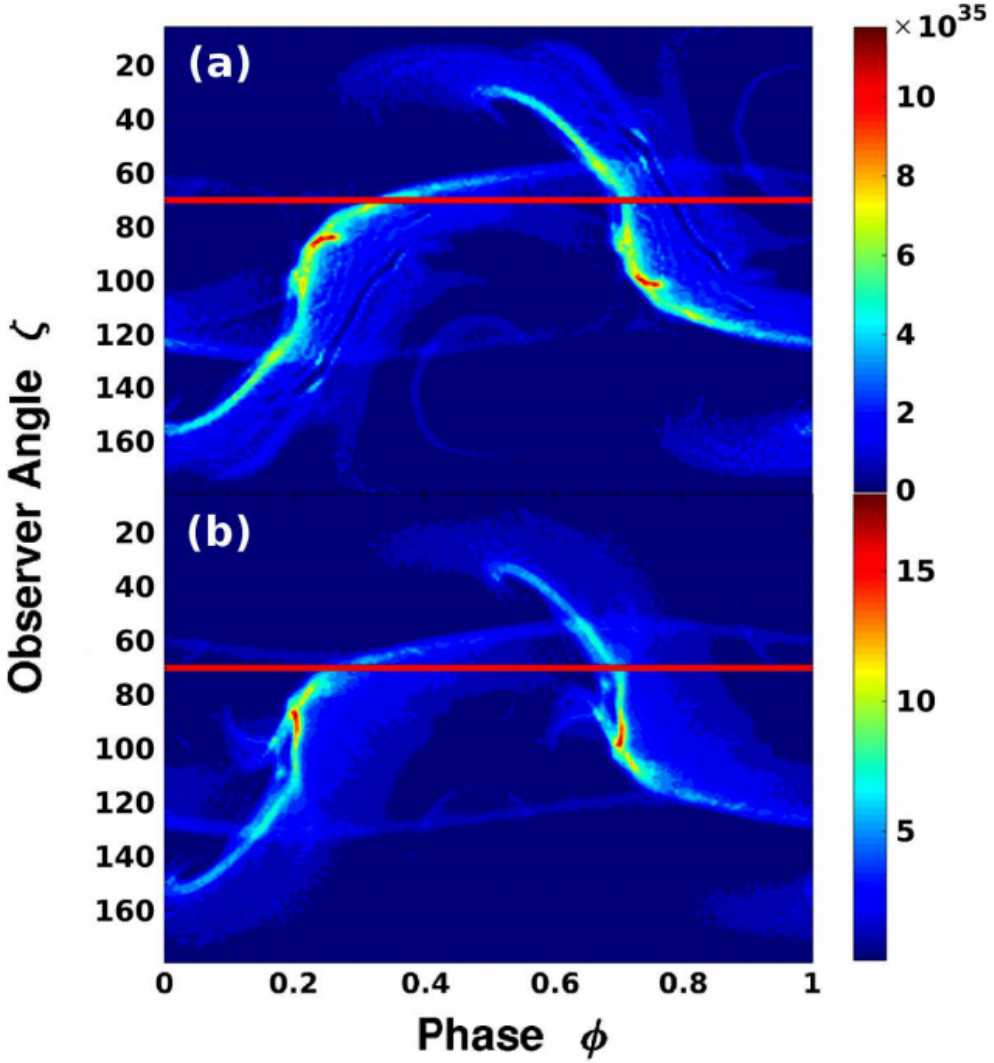
Refinement of Curvature Radius ρ_c

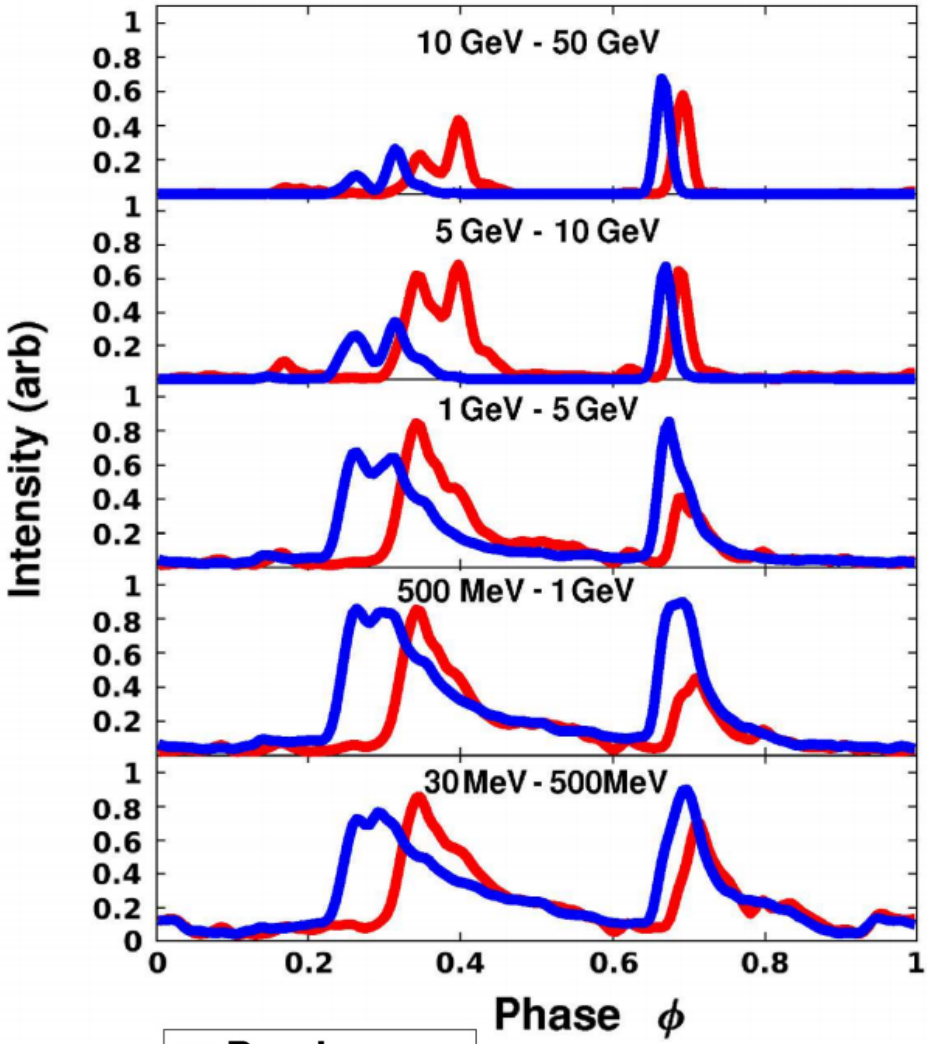


Barnard et al. (in prep)

Refinement of Curvature Radius ρ_c

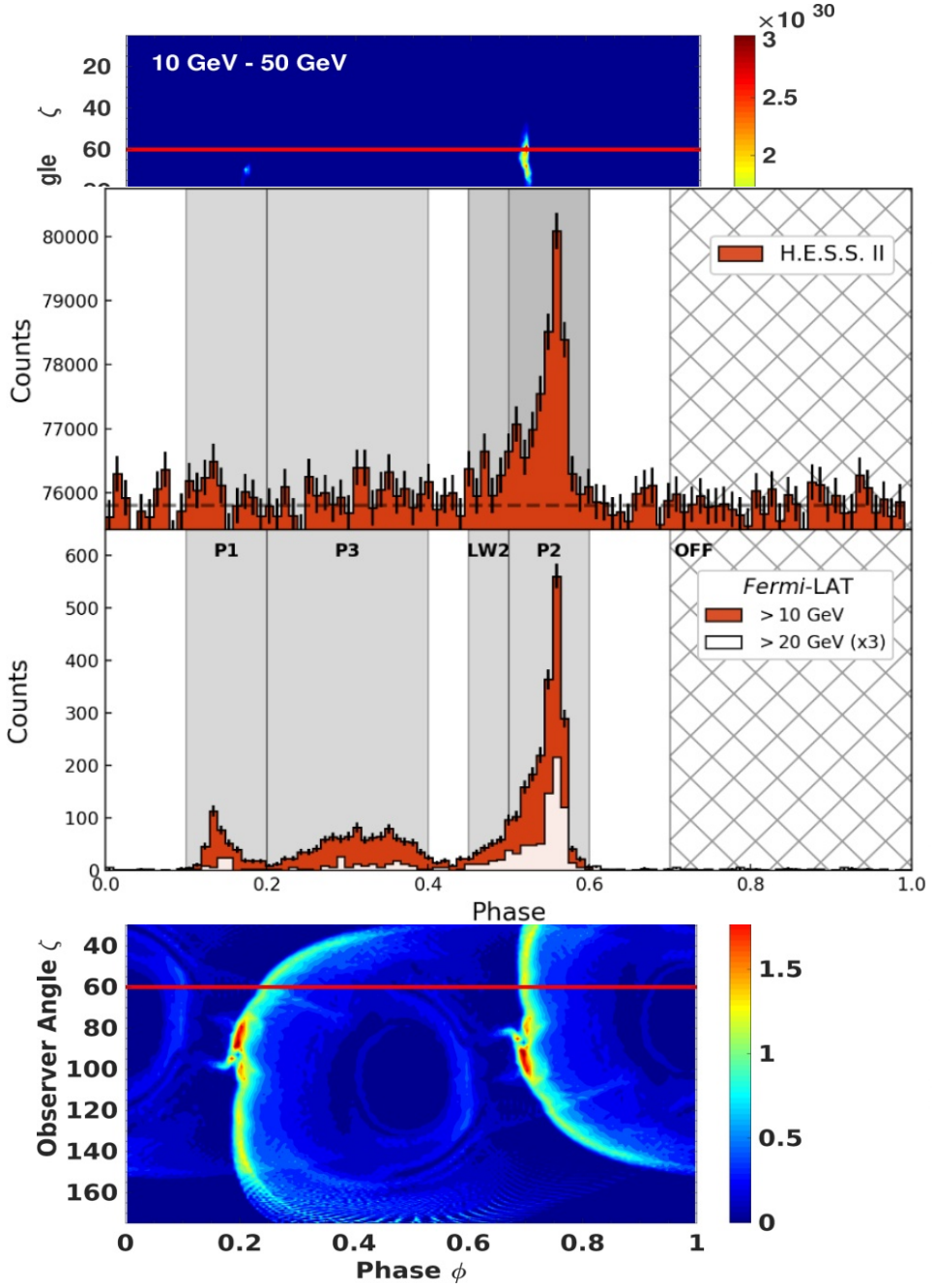
$\alpha = 45^o$, $\zeta = 70^o$, 30 MeV – 50 GeV

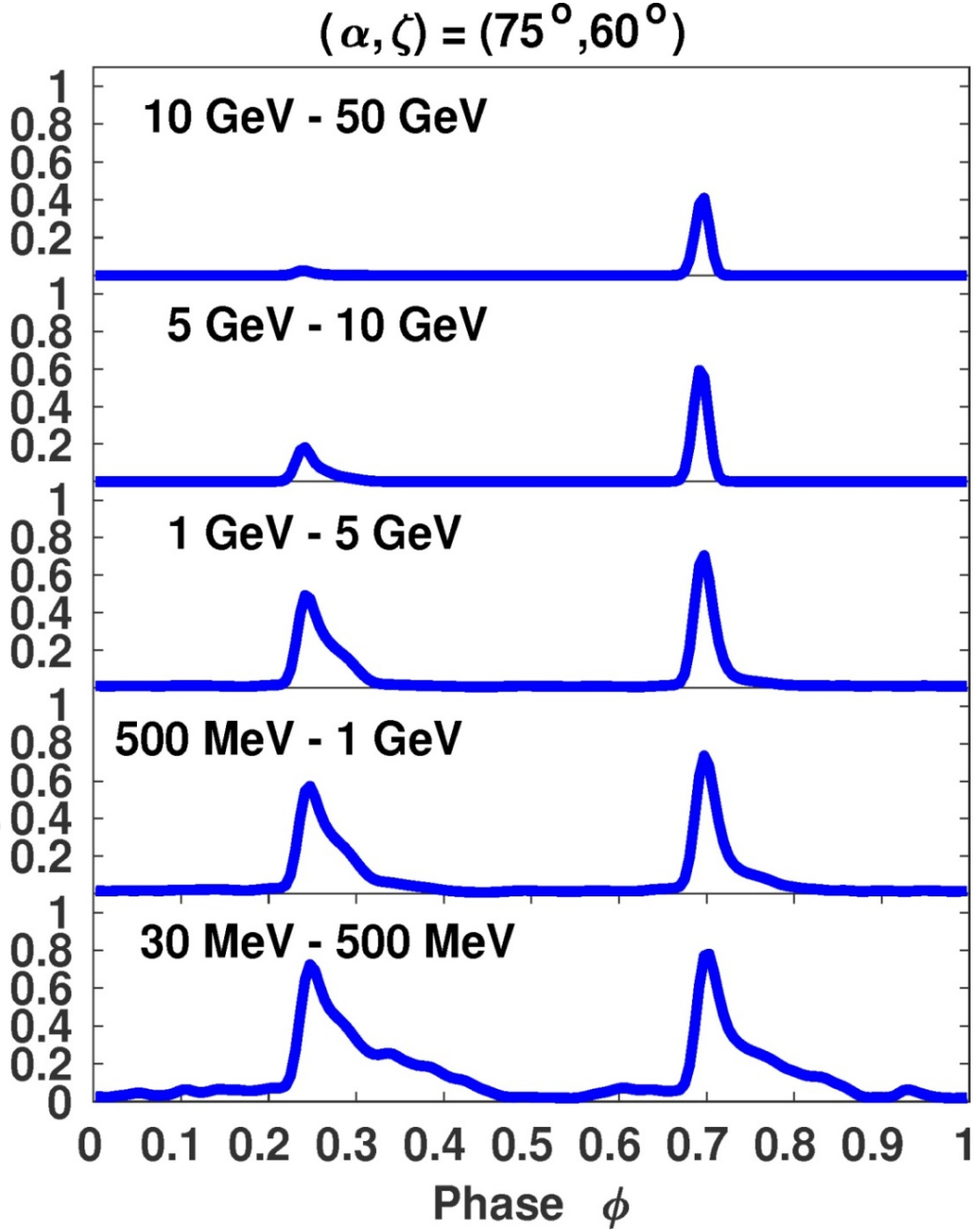




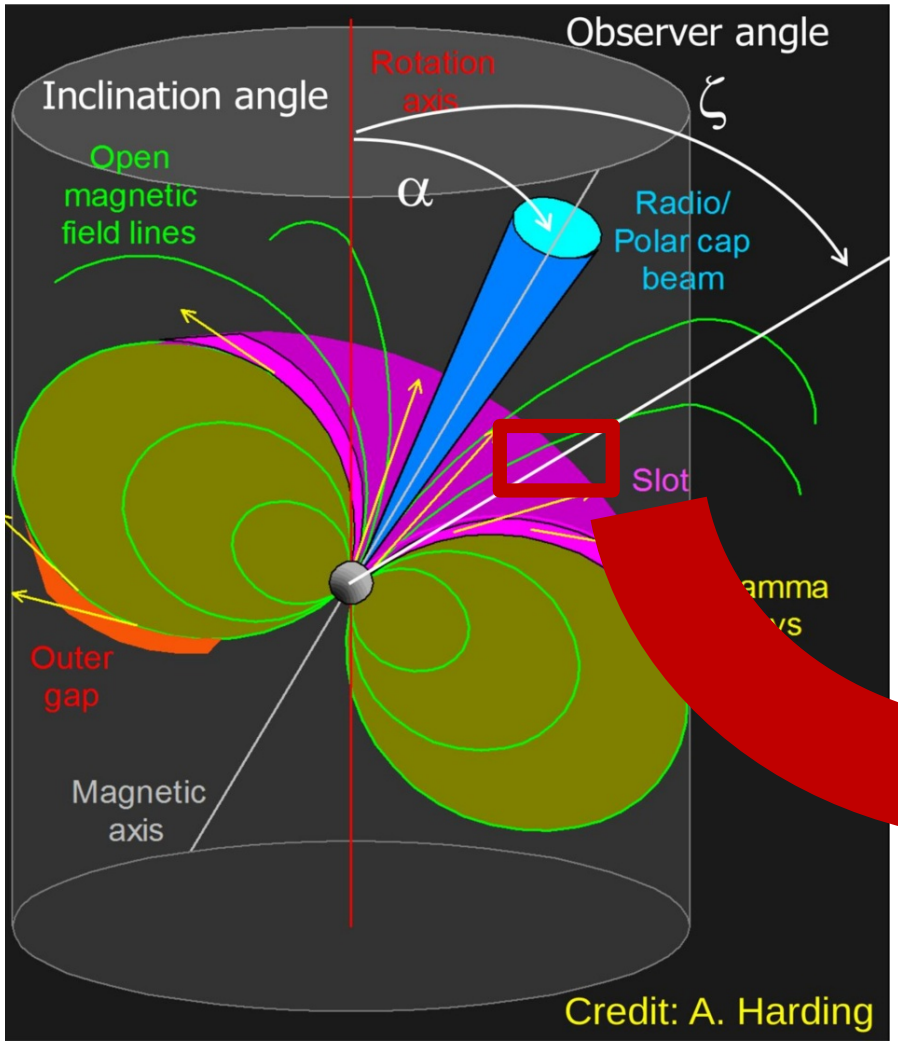
Barnard et al. (in prep)

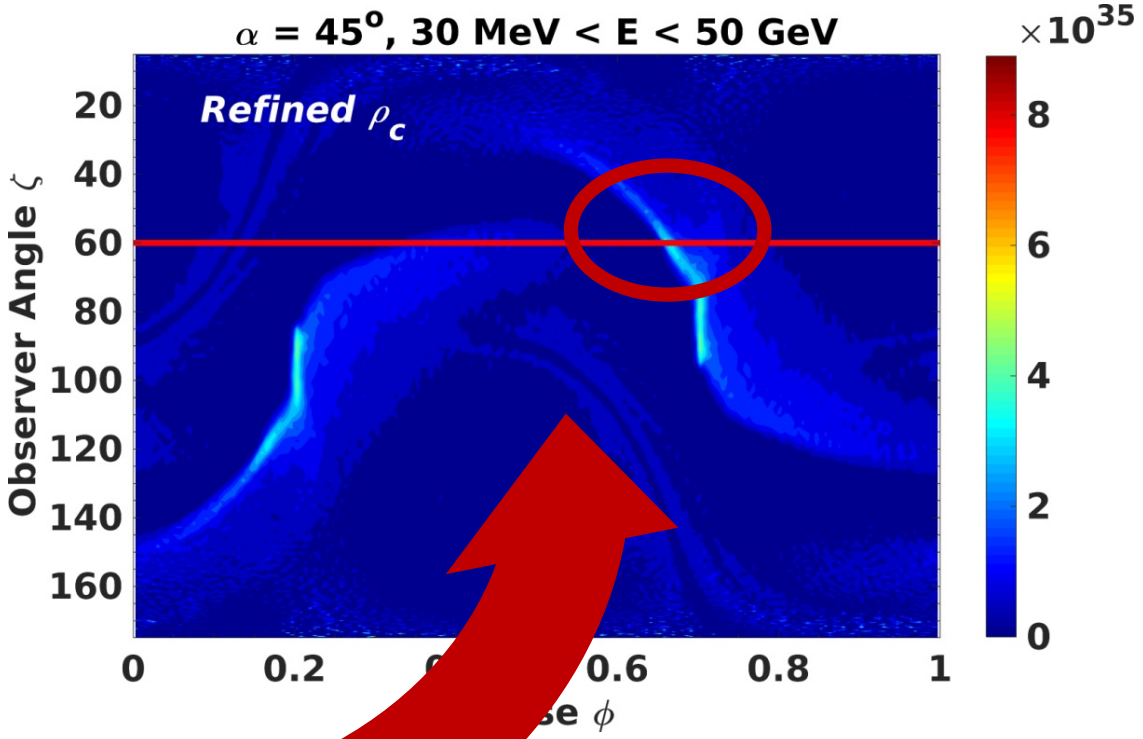
Energy-dependent CR light curves



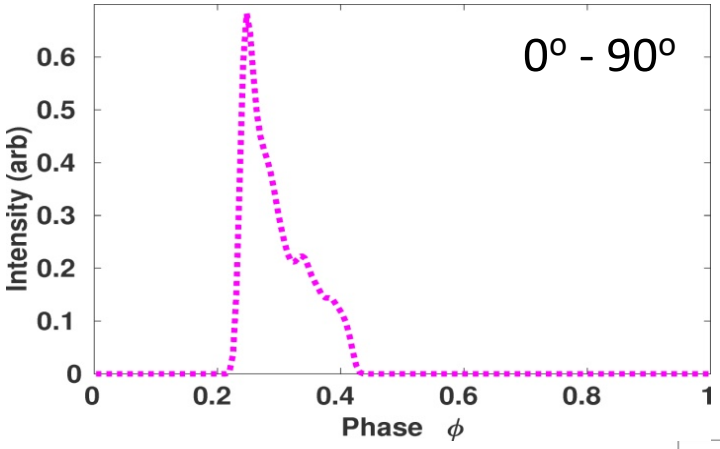


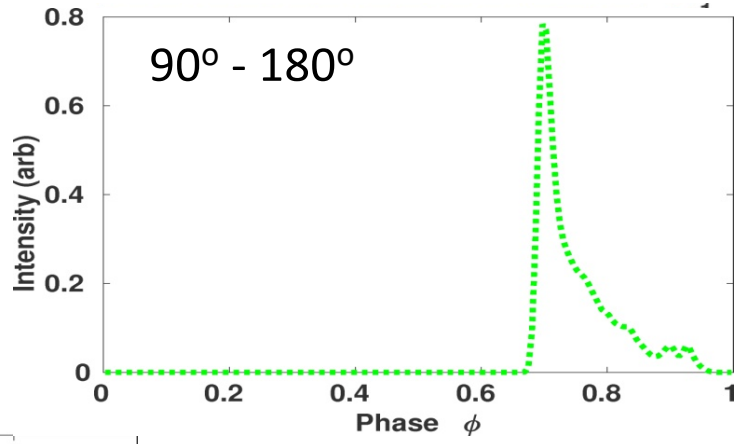
Isolating the Effect: Forward Mapping

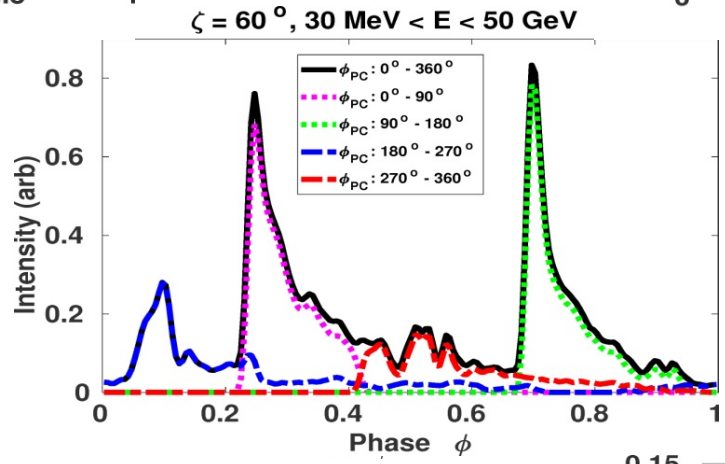


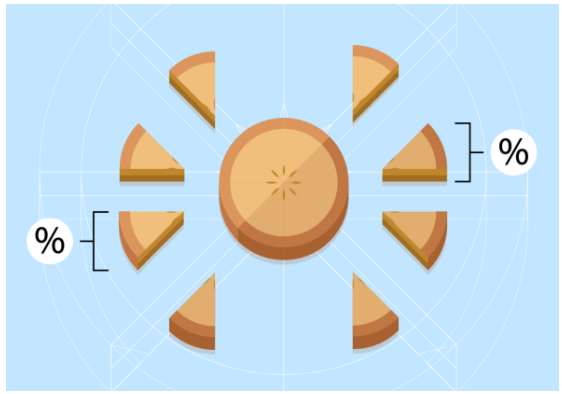


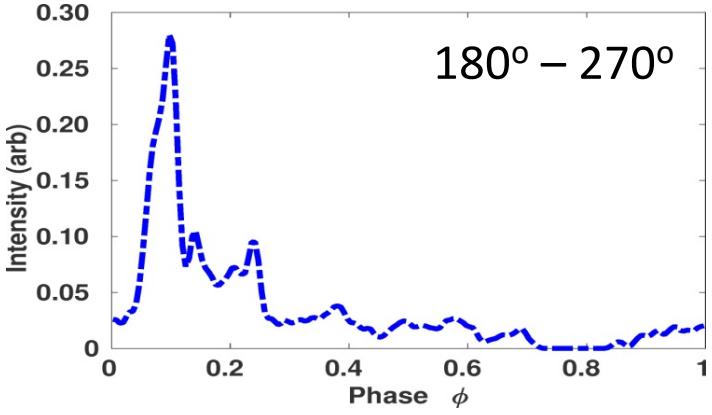
First attempt: Isolating the Effect (ϕ_{PC})

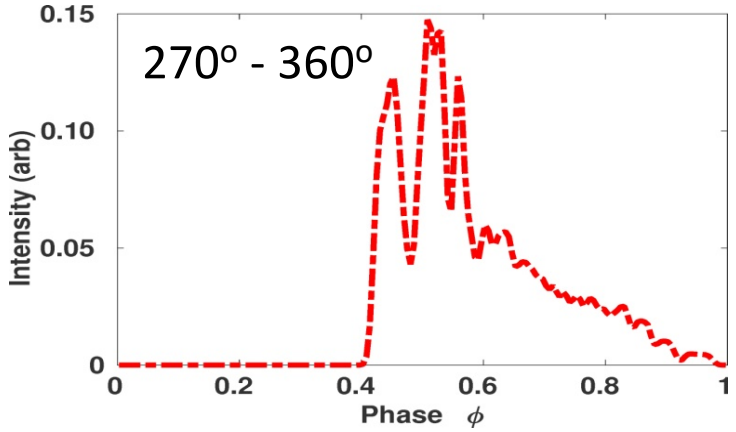




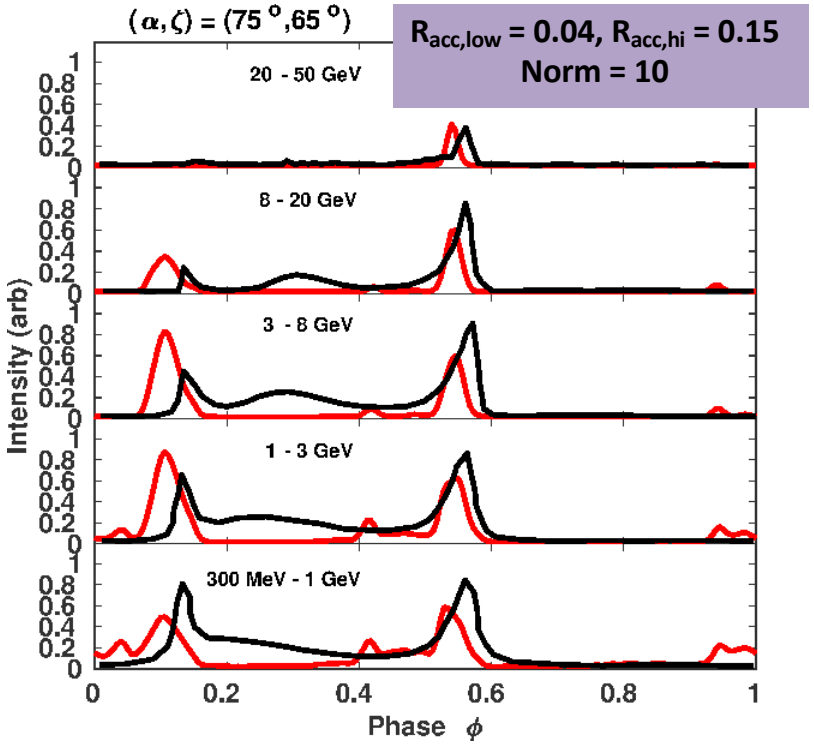


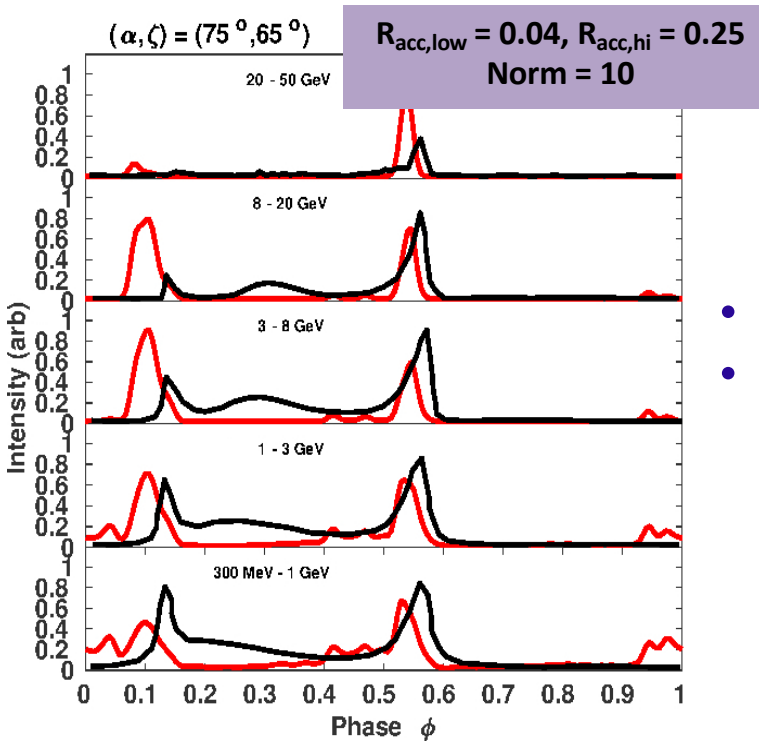




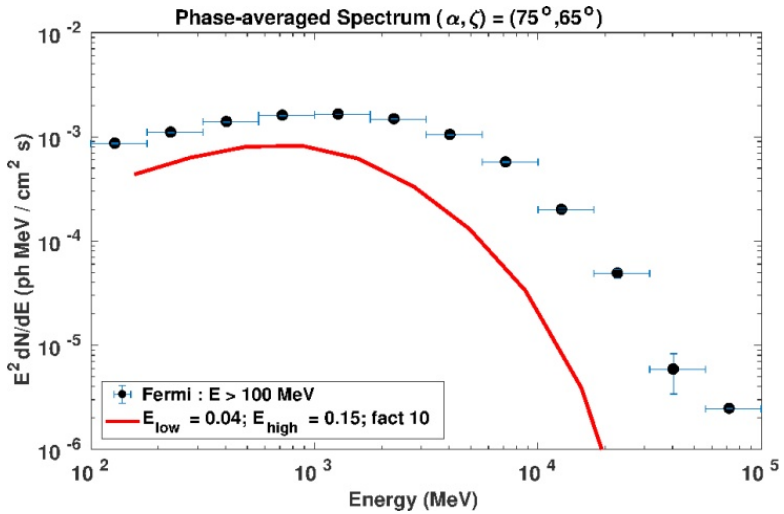


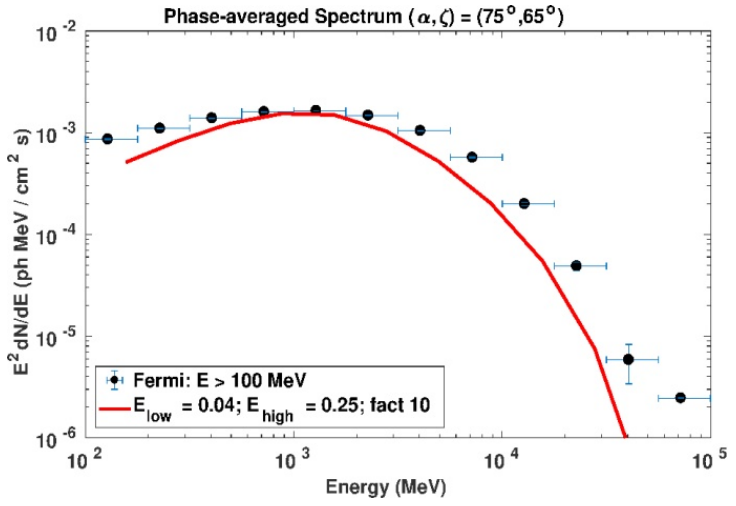
First Fit Spectrum + LCs





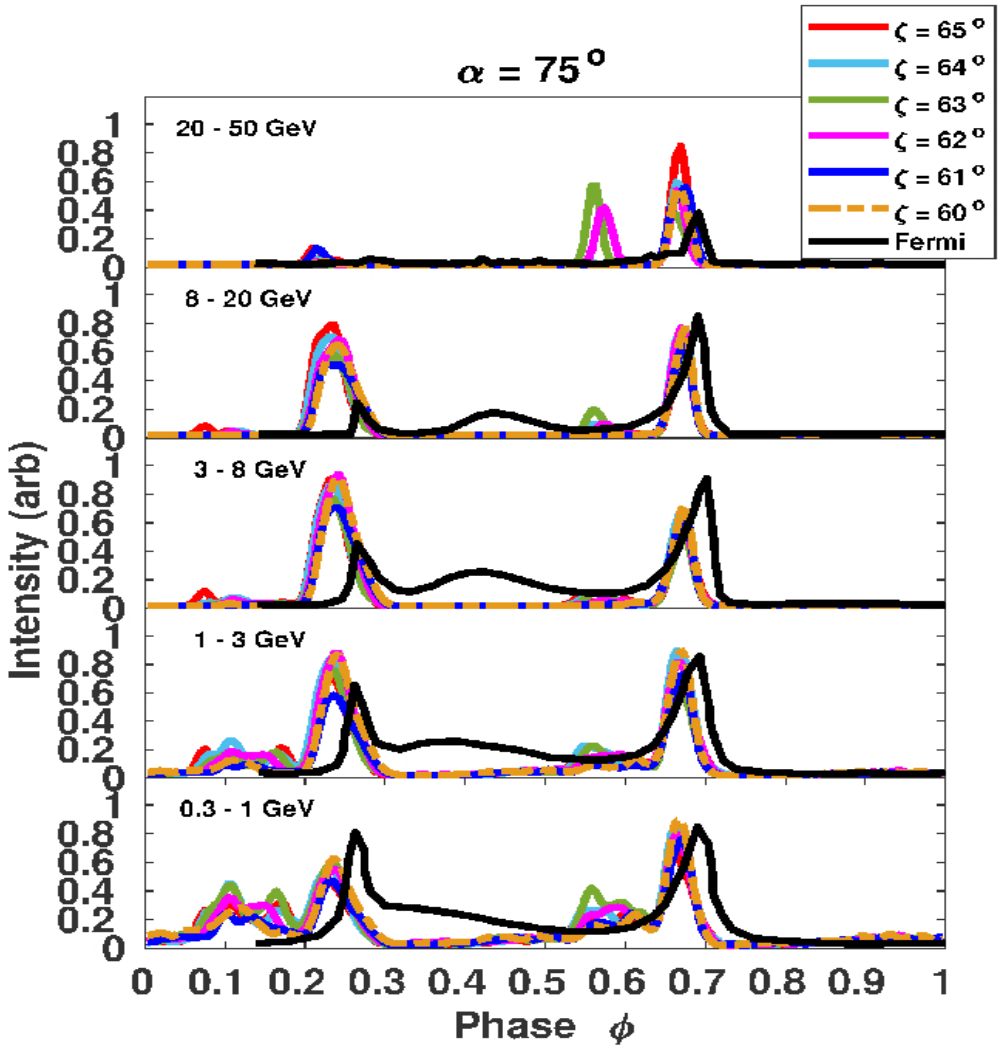
- Two-step $E_{||}$
- Tension between spectral and energy-dependent LC fits



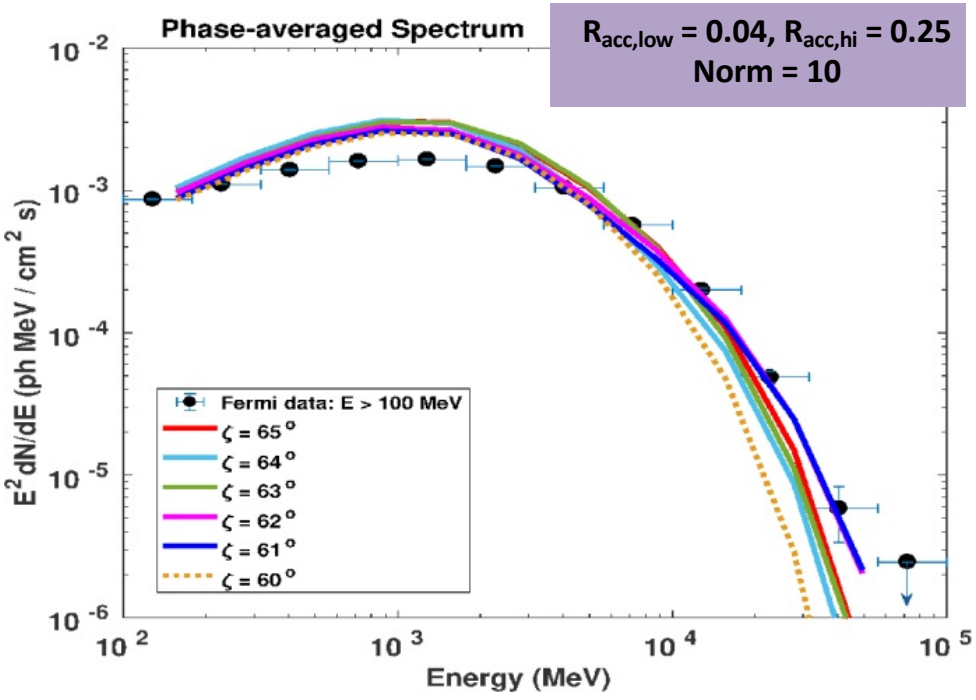


$R_{acc} = eE_{||}/mc^2$

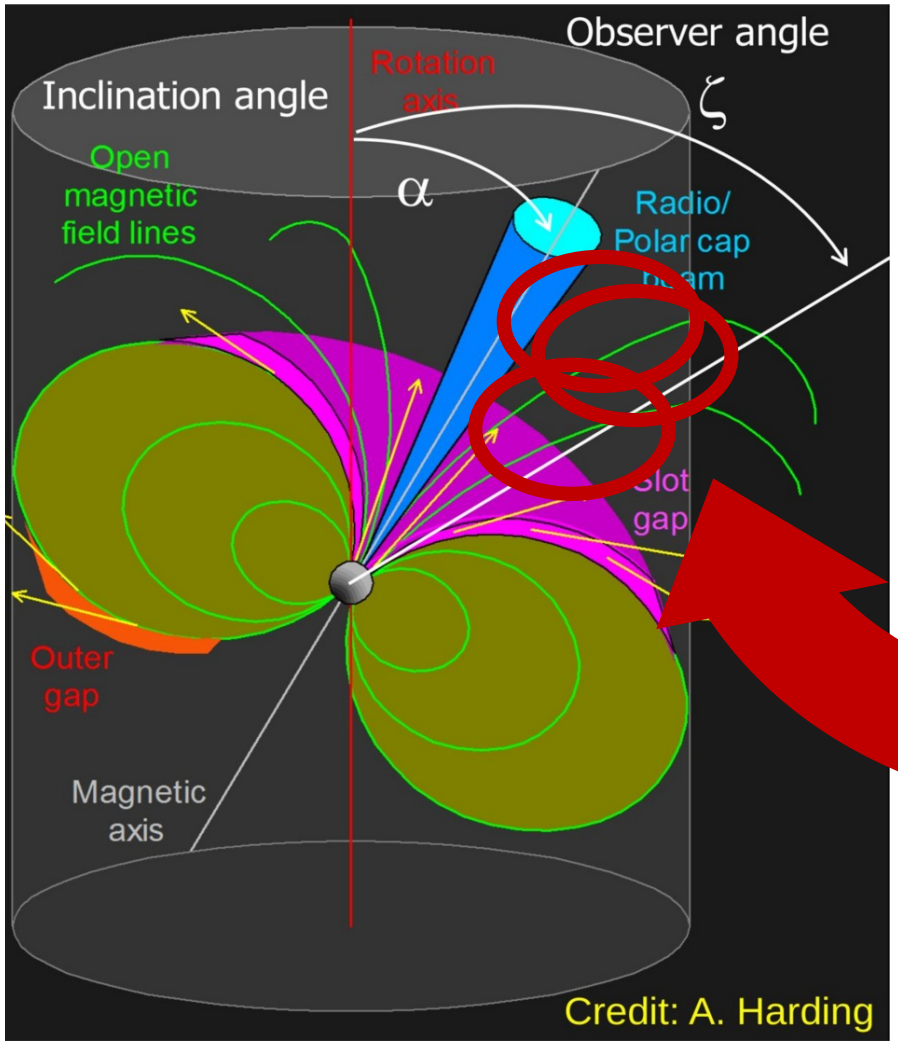
First Fit Spectrum + LCs

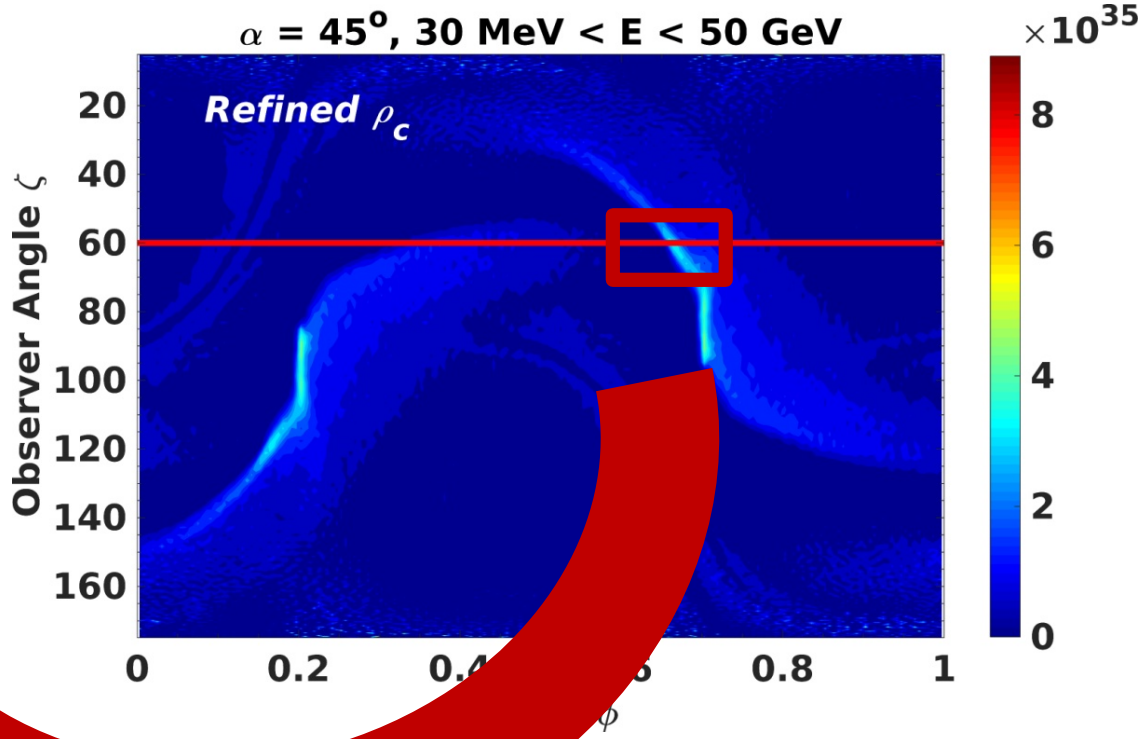


Fine tuning:
ζ dependence



Isolating the Effect: Reverse Mapping

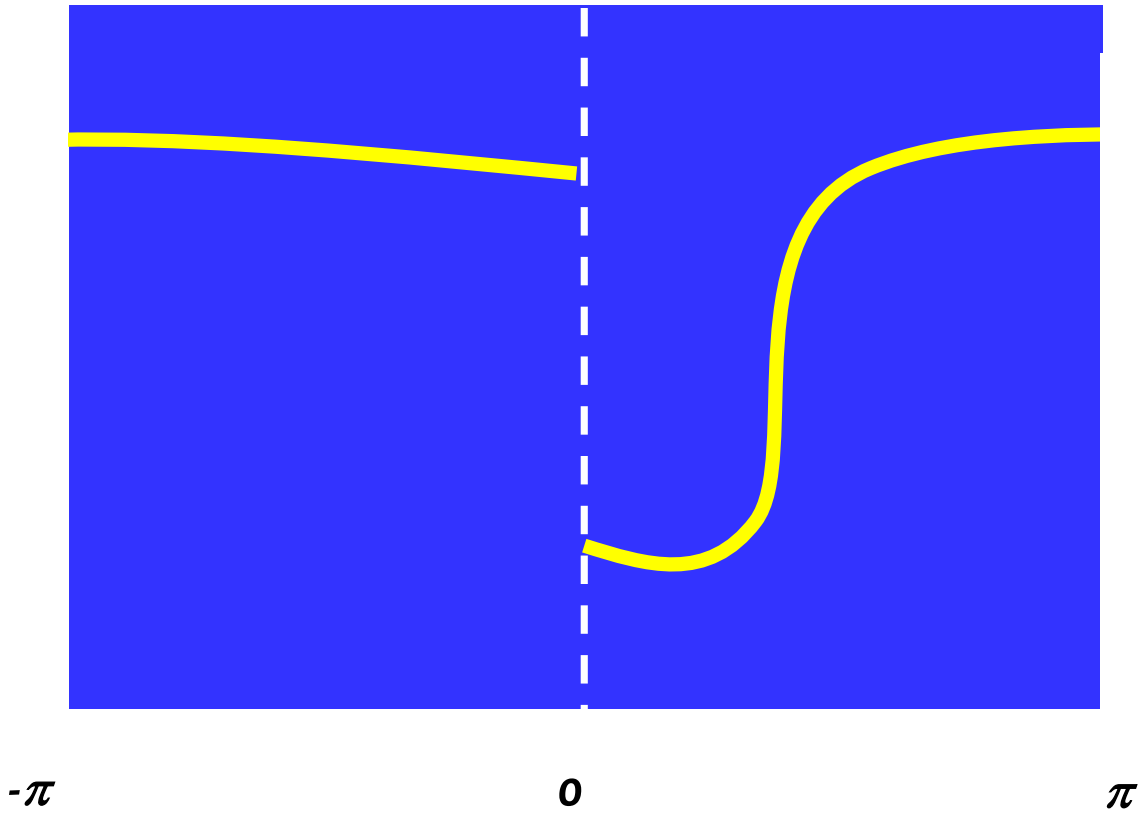




Second Attempt
Isolating the Effect (ζ and ϕ)

Directly in code:

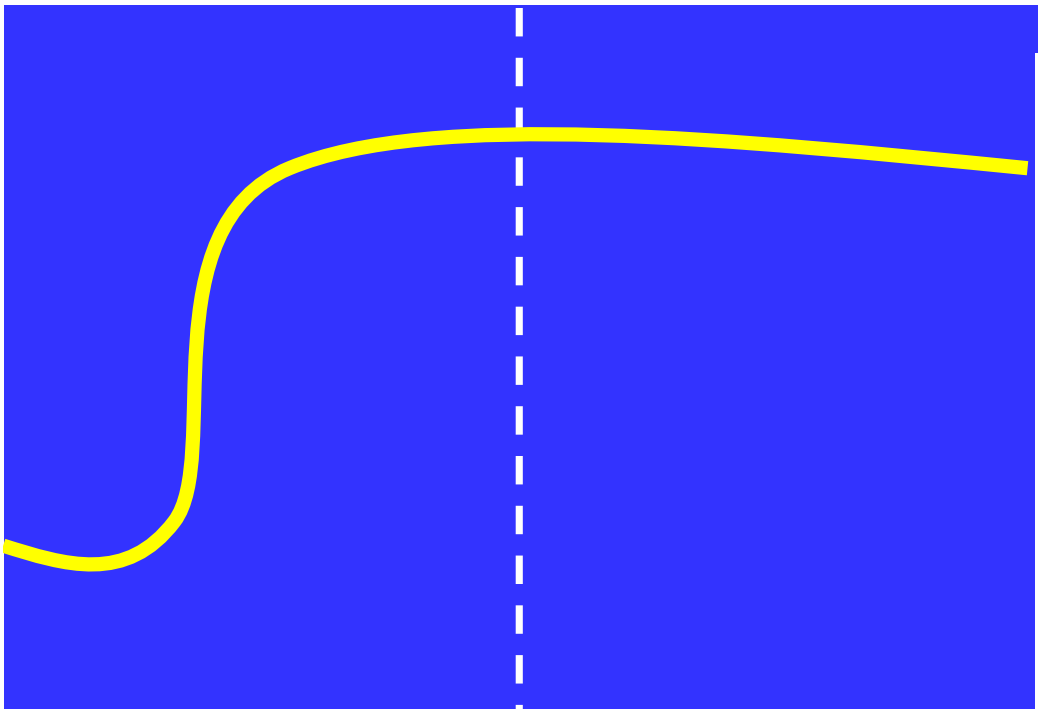
- ***Only north pole simulated***



Second Attempt
Isolating the Effect (ζ and ϕ)

Cyclic:

- ***Move by 1 rotation***
- ***Normalise ϕ***

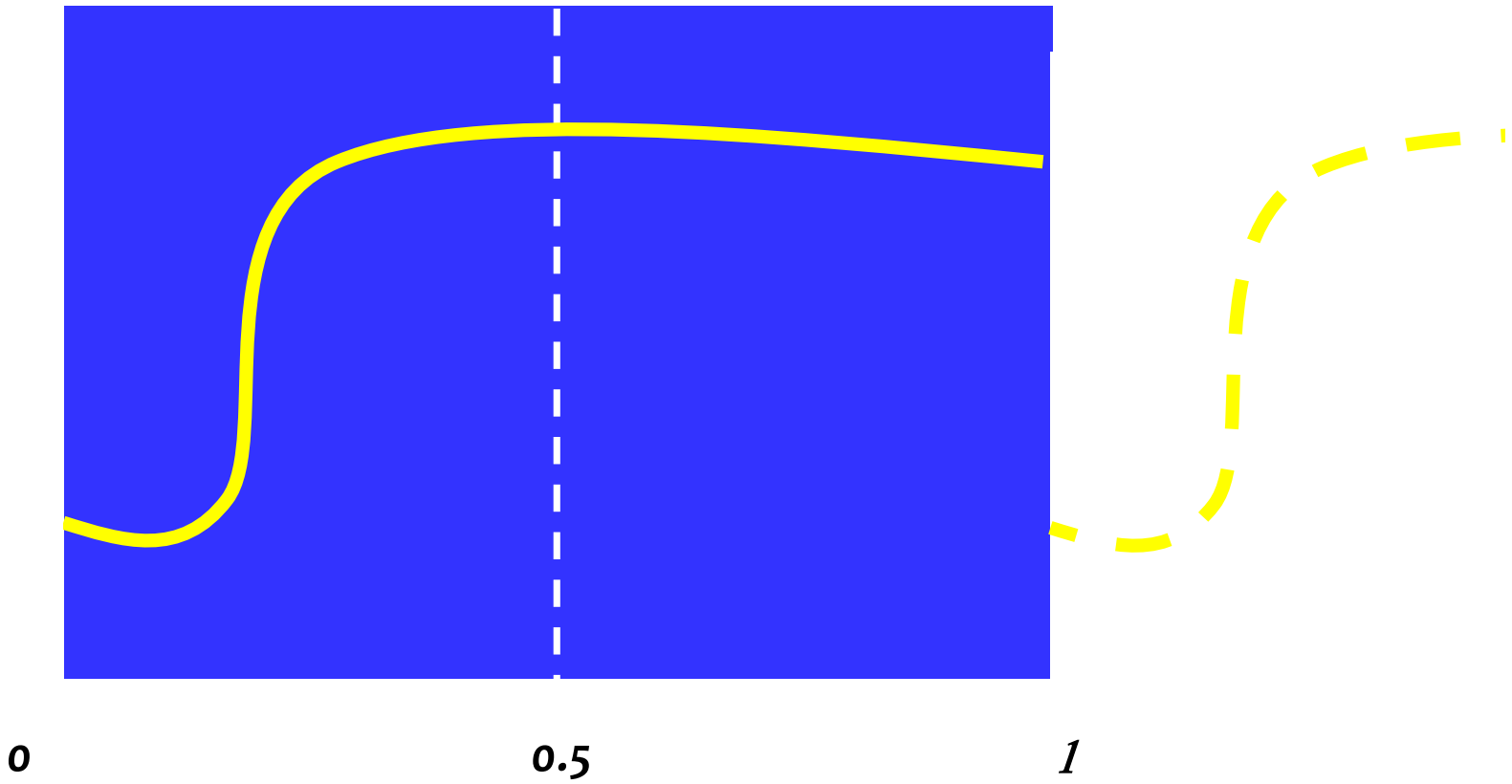


0 ***0.5*** ***1***

Second Attempt
Isolating the Effect (ζ and ϕ)

South pole:

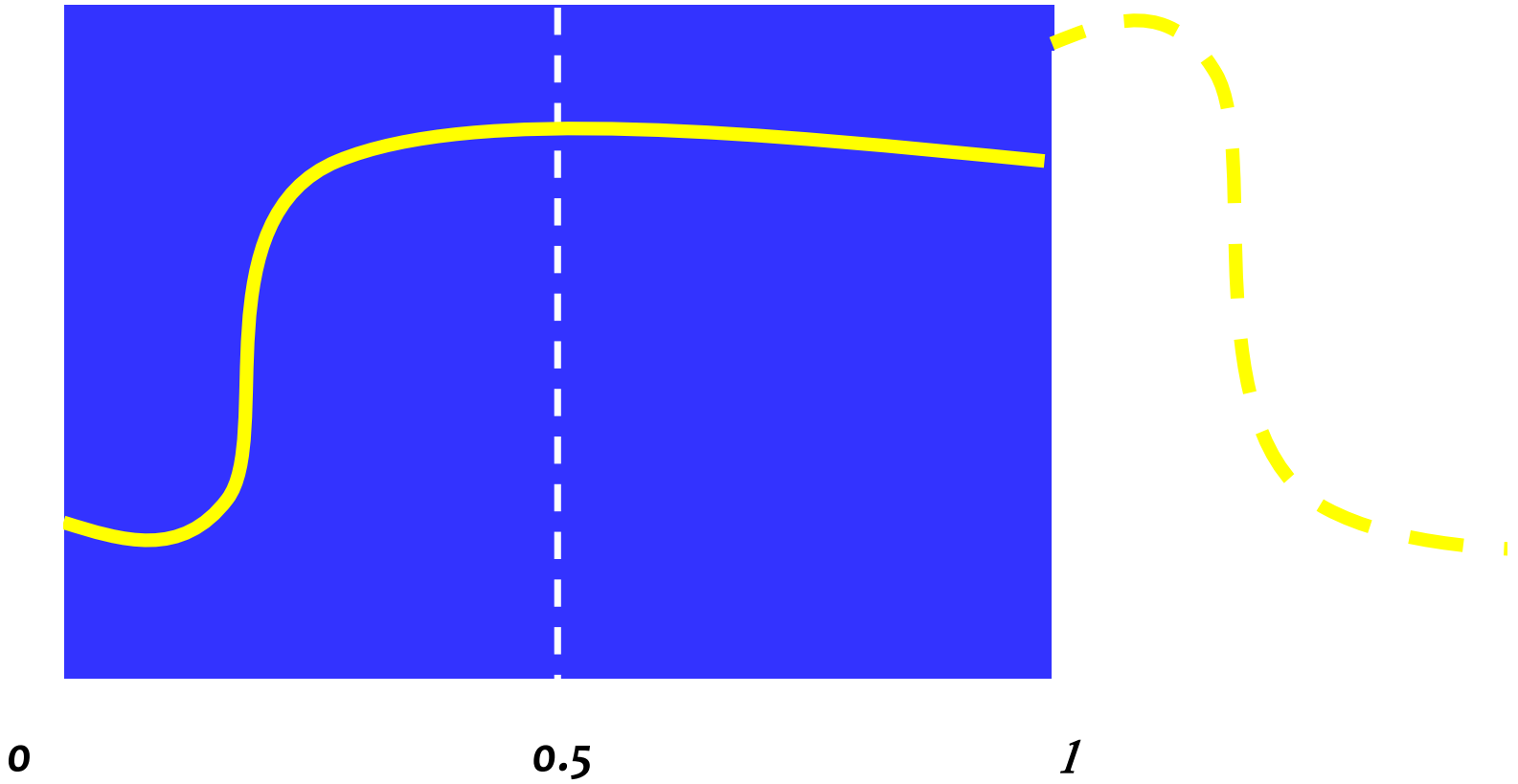
- ***Move by 1 rotation***



Second Attempt
Isolating the Effect (ζ and ϕ)

South pole:

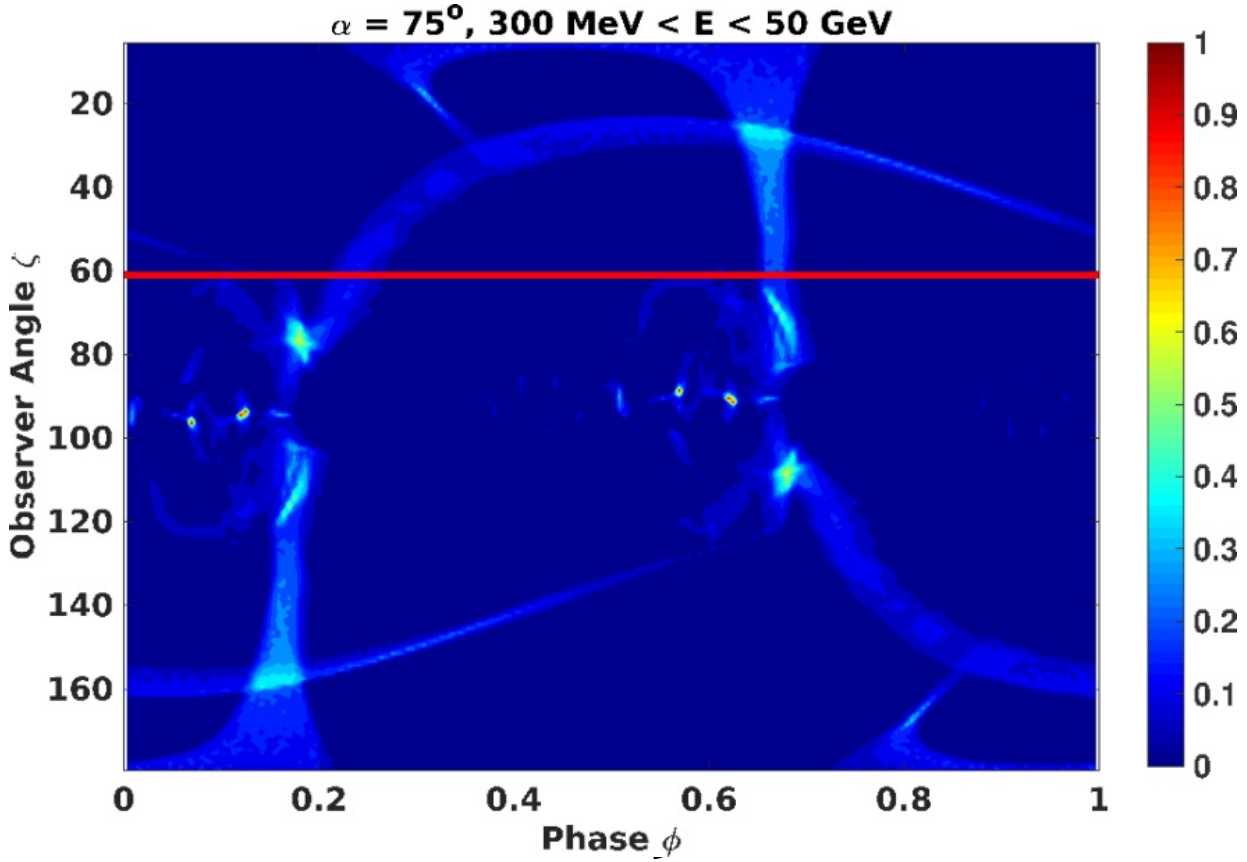
- ***Flip***



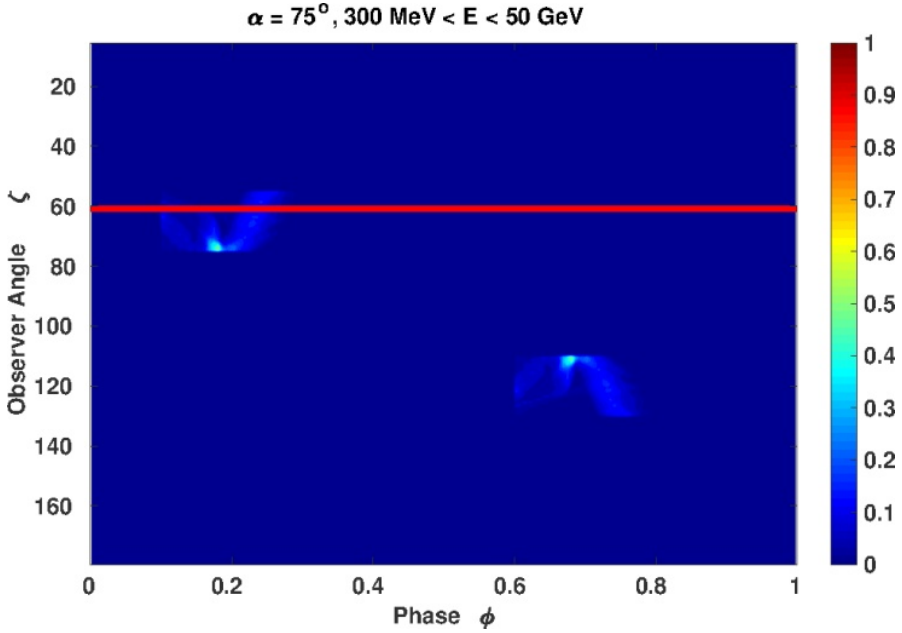
Second Attempt
Isolating the Effect (ζ and ϕ)

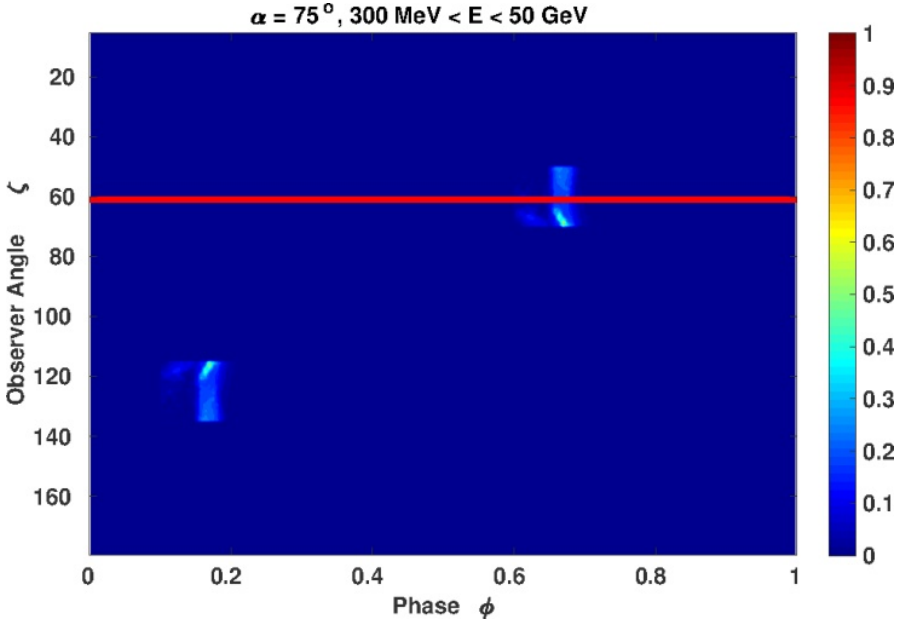
South pole:

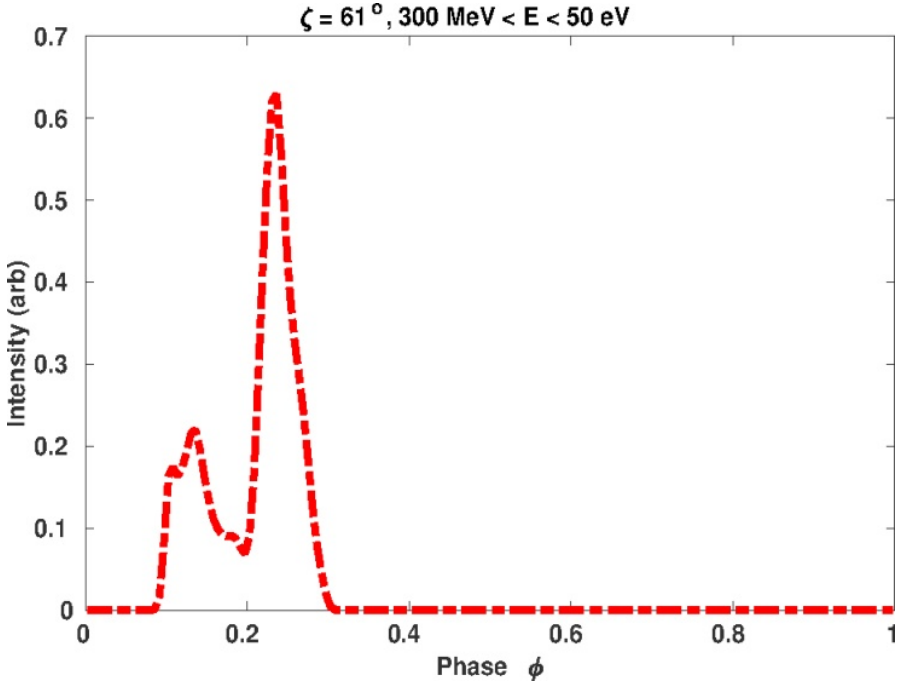
- ***Move back by half a rotation***

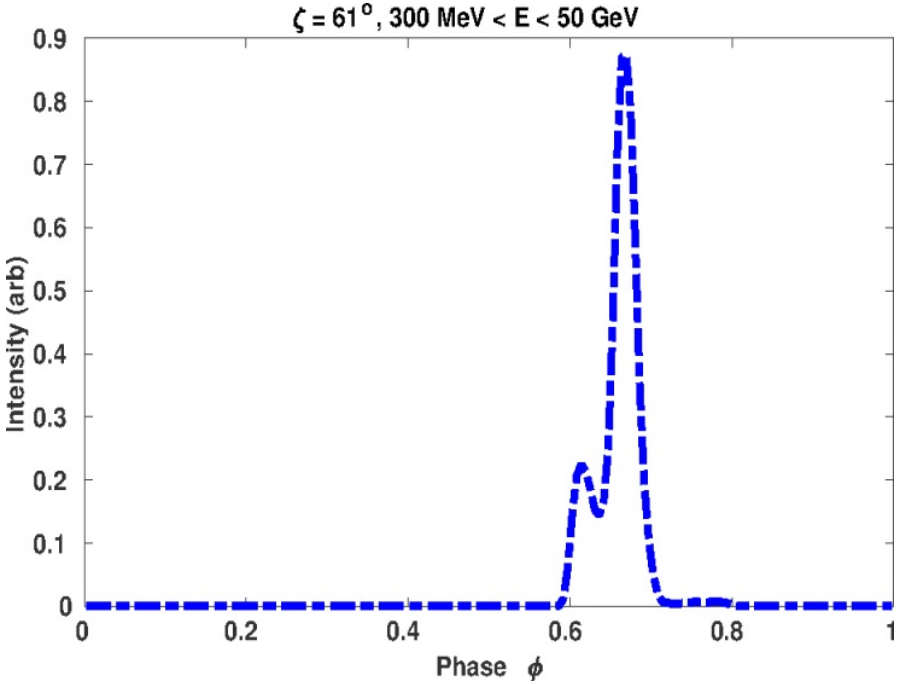


Isolating the Effect (ζ and ϕ)



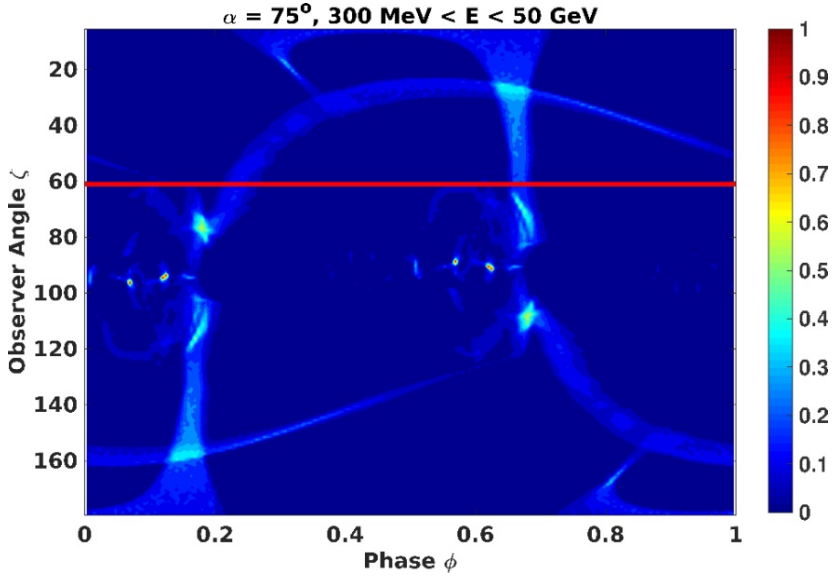


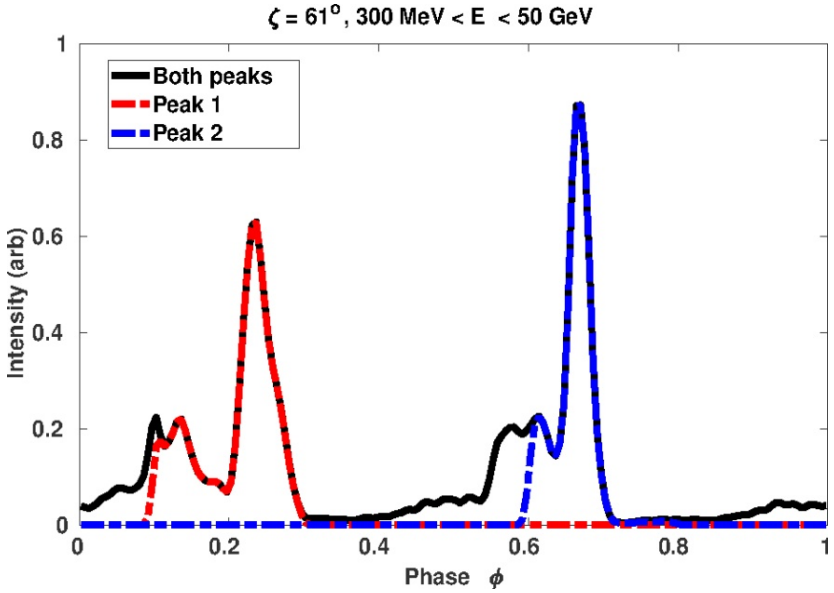


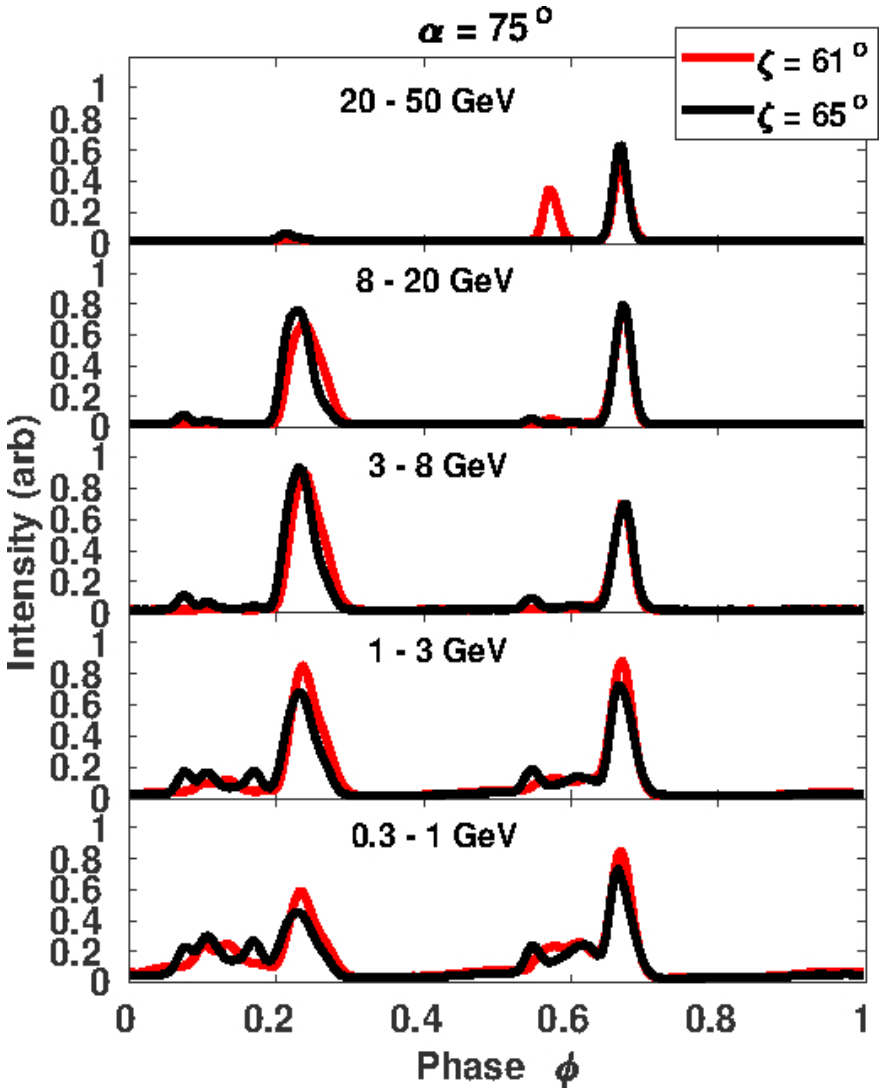


Finer Resolution

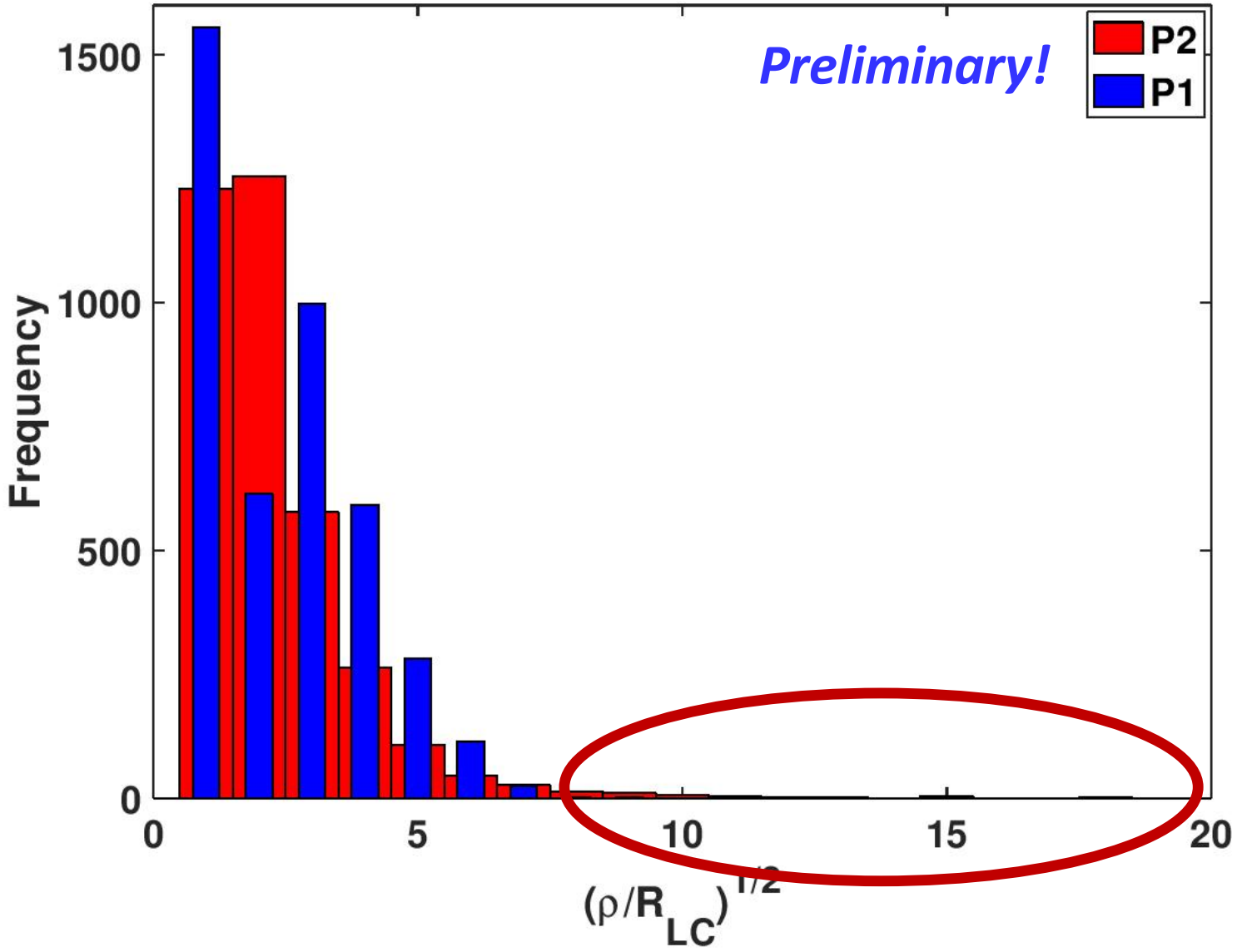
(720 azimuthal divisions, 11 colatitude divisions)



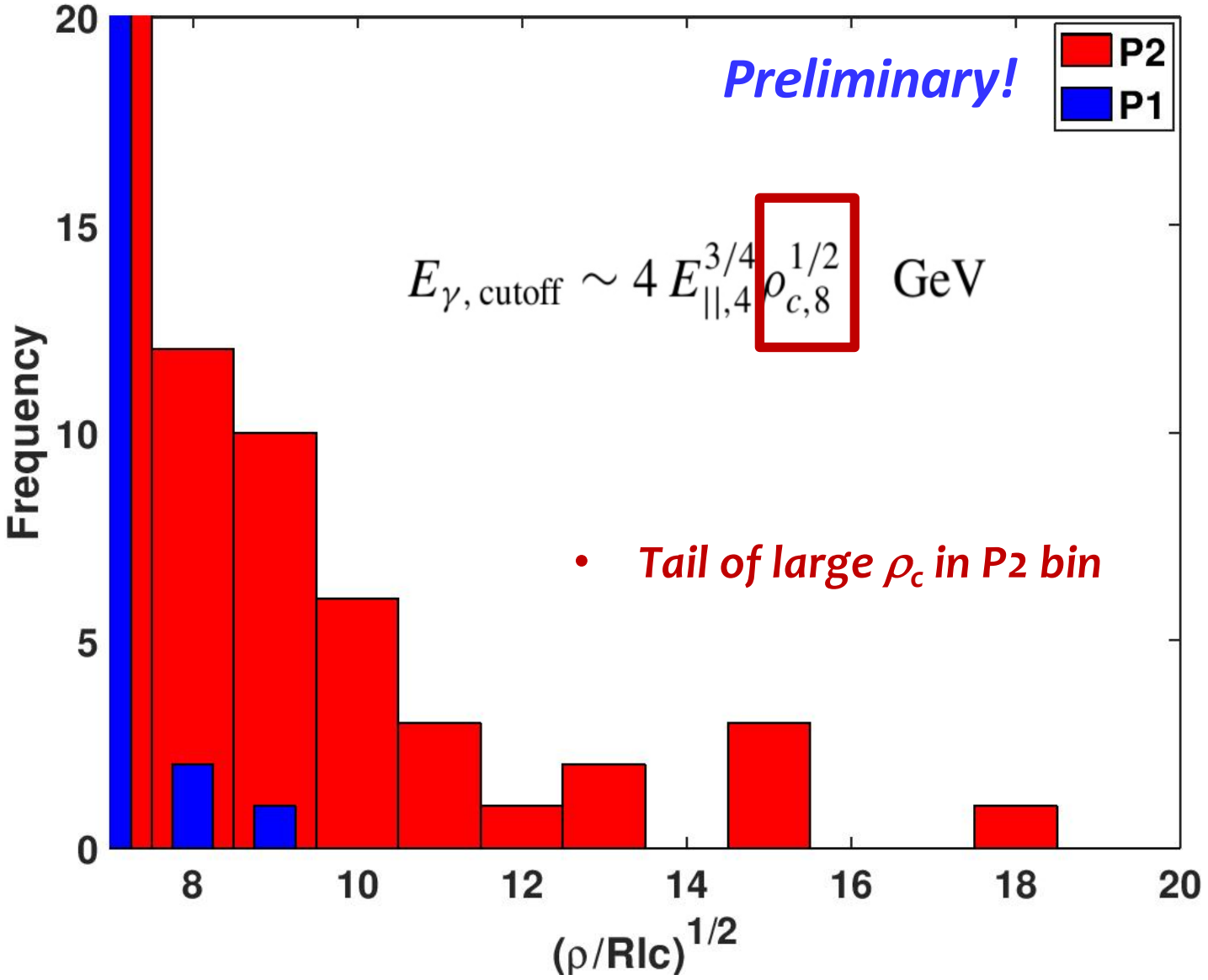




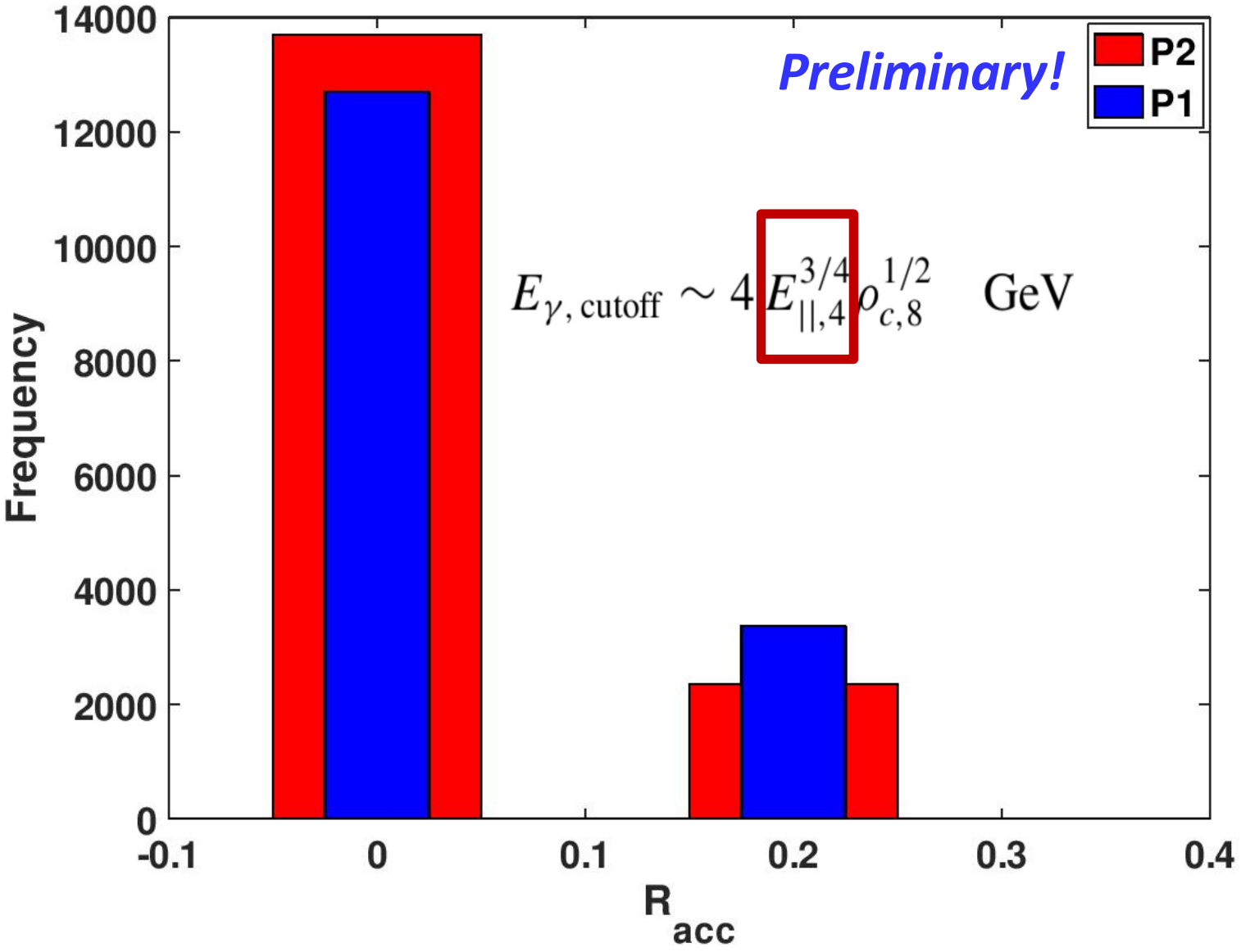
Distribution of ρ_c



Distribution of ρ_c



Distribution of $E_{||}$ or R_{acc}



Conclusions

- **Three pulsars detected in VHE band so far**
- **New component, or extension of GeV one?**
- **For Vela, P1/P2 ratio decreases with energy: P2 spectrum must have larger cutoff. Probe emission mechanism?**
- **Isolating effect: reverse mapping.**
- ***Preliminary*** **findings: P2 has systematically larger ρ_c, but also systematically larger local B-field. More work needed!**

Thanks!

This work is based on the research supported wholly/in part by the National Research Foundation (NRF) of South Africa (grant number 99072). The grantholder acknowledges that opinions, findings, and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the author(s), and that the NRF accepts no liability whatsoever in this regard.

"O LORD our Lord, how majestic and glorious and excellent is Your Name in all the earth! You have displayed Your splendour above the heavens" **(Psalm 8:1 AMP).**